İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

LOCALIZATION AND ITS EFFECTS ON DATA DELIVERY IN UNDERWATER SENSOR NETWORKS

Ph.D. Thesis by
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Programme : Computer Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

SUALTI DUYARGA AĞLARINDA KONUMLANDIRMA VE KONUMLANDIRMANIN VERİ DAĞITIMINA ETKİSİ

DOKTORA TEZİ

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FOREWORD

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September 2009 Melike Erol
Computer Engineer, M.Sc

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ABBREVATIONS

USN	:	Underwater Sensor Network
MUSN	:	Mobile Underwater Sensor Network
AUV	:	Autonomous Underwater Vehicle
DNRL	:	Dive aNd Rise Localization
PL	:	Proxy Localization
LSL	:	Large Scale Localization
MANET	:	Mobile Ad Hoc Network
MCM-SE	:	Meandering Current Mobility with Surface Effect
LBL	:	Long Base Line
RF	:	Radio Frequency
MAC	:	Medium Access Control
AODV	:	Ad hoc On-Demand Distance Vector
RREQ	:	Route Request
RREP	:	Route Reply
RERR	:	Route Error
GPSR	:	Greedy Perimeter Stateless Routing
RTS/CTS	:	Request to Send / Clear to Send
CBR	:	Constant Bit Rate
GPS	:	Global Positioning System
ONR	:	Office of Naval Research
RSSI	:	Received Signal Strength Indicator
AoA	:	Angle of Arrival
TDoA	:	Time Difference of Arrival
SOFAR	:	Sound Fixing And Ranging
LAR	:	Location-Aided Routing
DTN	:	Delay Tolerant Network
VAR	:	Velocity-Aided Routing
PMLAR	:	Predictive Mobility and Location-Aware Routing
DFR	:	Direction Forward Routing
PBR	:	Prediction-Based Routing
FBR	:	Focused Beam Routing
VBR	:	Vector-Based Forwarding
HH-VBR	:	Hop-by-Hop Vector Based Forwarding
MVS	:	Multipath Virtual Sink
LASR	:	Location-Aware Source Routing
TDMA	:	Time Division Multiple Access
DDD	:	Delay Tolerant Data Dolphins
PULRP	:	Path Unaware Layered Routing Protocol
E-PULRP	:	Energy Optimized path Unaware Layered Routing Protocol

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ψ	:	Stream function
η	:	Confidence value
ε	:	Estimation error
φ	:	Coordinate estimate vector
λ	:	Inverse of the decorrelation time
U	:	Root-mean-square of the wind speed
ω	:	Central frequency of the meanders
(u,v)	:	Horizontal velocity vector
$w(t)$	:	Wiener process
ξ_i	:	Noise

LOCALIZATION AND ITS EFFECTS ON DATA DELIVERY IN UNDERWATER SENSOR NETWORKS

SUMMARY

Underwater Sensor Networks (USN) are emerging as promising tools to enable a wide range of oceanographic missions, presently not possible or very costly, such as: oceanographic floor exploration, ecological applications, military underwater surveillance, earthquake/tsunami forewarning, water pollution detection, monitoring oil drilling sites and mine reconnaissance missions.

The architecture of the USN depends on the application. For example, monitoring oil drilling sites or littoral water surveillance require stationary USNs with tethered sensor nodes, whereas chemical spill detection demands a mobile USN with untethered, free-floating sensor nodes. The USN may also have a hybrid architecture including both sensors and mobile equipments such as, Autonomous Underwater Vehicles (AUV), Autonomous Surface Vehicles (ASV), Supervised Underwater Vehicles (SUV), gliders and underwater robots. These varying applications and architectures determine the necessary protocols for the operation of USNs. Localization is essential in these types of USN applications.

Localization is basically knowing where a node is, either in terms of latitude, longitude, altitude or relative position to peers. Location information is essential for data tagging, target detection and node tracking. Besides data collection and tagging, a sensor network also needs to deliver the collected data to a central station. Moreover, new applications require the sensor nodes communicate among each other to establish a coordinated task. Therefore data delivery and medium access arises as other significant issues. Depending on the application, reliable end-to-end delivery can become significant, as well. Localization, medium access, data delivery are studied much in terrestrial sensor networks. However, the techniques in terrestrial sensor networks are not efficient for USNs, mostly due to the challenges of underwater communication.

Underwater networking is viable with acoustic communications. The acoustic channel has low bandwidth. Hence, low data rate, high propagation delay, high bit error rate and the acoustic signals face multipath effects together with the time varying properties. Currently, short-range acoustic underwater modems can achieve bit rates around 20-50 kbit/s. The speed of sound is approximately 1500m/s and it varies with dynamic properties of the ocean such as temperature, salinity and density. Reflections from the surface or the ocean floor cause multipath propagation. Moreover, the displacement of surface waves cause time varying propagation properties.

The challenges of acoustic communication demand robust signal processing techniques at the physical layer. On the other hand, large propagation delay, limited bandwidth, energy efficiency affect the design of the upper layers of the protocol stack. Besides the challenges related to the acoustic communications, motion is an inherent property of the USN, and it affects the design of the network protocols.

In the literature, there are previous works that focus on data gathering, synchronization, localization, routing and medium access issues for USNs. Most of these works are simulation studies since deploying USNs are costly.

In this thesis, we focus on localization and data delivery for USNs. Although there are localization solutions for terrestrial sensor networks, it becomes challenging in USNs due to several reasons. First, Global Positioning System (GPS) is not available below the surface level of the ocean. Second, localization without using GPS requires a large amount of packet exchange which may be unaffordable for the USN. Tight energy limitations also enforce minimum protocol overhead. Third, mobility necessitates periodic localization.

In this thesis, we propose two localization algorithms and compare their performance with a recognized technique from the literature. Our proposals are Dive aNd Rise Localization (DNRL) and Proxy Localization (PL). The DNR Localization (DNRL) uses several special nodes that are able to dive and rise in the water column by using a volume expansion technique. The DNR beacons learn their coordinates from GPS and during ascending or descending they announce their coordinates at several intervals. An underwater node uses the coordinates of the DNR and makes lateration to estimate self location. Proxy Localization (PL) adds an iterative approach to DNRL and enables the successfully localized underwater nodes to become location proxies for their non-localized one hop neighbors. We compare the performance of DNRL and PL with the Large-Scale Localization (LSL) method. The reason for comparing DNRL and PL with LSL is that they aim to solve the localization problem for similar USN architectures. They are all distributed and suitable for large-scale mobile USNs. LSL employs three types of nodes. “Surface buoys” float on the surface and periodically send the GPS driven coordinates to “anchor nodes”. Anchor nodes float underwater and are scattered among the “ordinary nodes” at several depths. Anchor nodes learn their coordinates from beacons via one hop, long-distance links. Then, they periodically broadcast self coordinates to their neighbors. In the LSL method, ordinary nodes are localized by lateration by using the coordinates of the anchor nodes that are one or two hops away. We compare the performance of DNRL, PL and LSL in terms of localization success, accuracy, overhead, energy consumption and delay. We use the Qualnet simulator with an acoustic physical layer.

Since we consider mobile and stationary USNs, a realistic mobility model is essential. In the oceans, free-floating objects move by the force of currents. We use the Meandering Current Mobility (MCM), model which models the subsurface currents, in addition with a surface layer mobility model. We use MCM with Surface Effects (MCM-SE) model to evaluate the performance of DNRL, PL and LSL with mobility.

In this thesis, we also study data delivery in underwater sensor networks. We investigate the performance of a location-based routing protocol. Since we propose localization approaches in our studies, it is natural to consider location-based routing for data delivery. We start our analysis by comparing the performance of a location-based routing protocol to a reactive topology-based routing protocol. We implement a greedy location-based protocol and use AODV as the reactive table-based routing protocol. We analyze the performance of the location-based protocol under localization inaccuracies. Localization protocols naturally have an estimation error and this has a negative impact on the delivery success of the location-based protocol.

As a result, we propose two distributed, large-scale, flexible localization schemes namely, DNRL and PL. We compare their localization success, accuracy, overhead, energy efficiency and delay with a technique from the literature, i.e. LSL. We show that DNRL outperforms the others in the mobile scenarios. In the stationary scenarios DNRL is advantageous in the sense of energy efficiency whereas LSL can be preferred for its higher delivery ratio. Fine-grained localization protocols have relatively low mean error ratios, so their use in a location-based routing protocol have slight impact on data delivery. If course-grained localization methods are used, the mean error ratio becomes high and the low accuracy values force the delivery ratio to decrease.

SUALTI DUYARGA AĞLARINDA KONUMLANDIRMA VE KONUMLANDIRMANIN VERİ DAĞITIMINA ETKİSİ

ÖZET

Sualtı Duyarga Ağları (SDA), oşınografik taban keşfi, ekolojik uygulamalar, askeri amaçlı sualtı gözleme, deprem/tsunami öngörüsü, su kirliliği tespit edilmesi, petrol çıkartma tesislerinin görüntülenmesi ve sualtı mayın keşfi gibi çok geniş bir alana yayılan ve şu an tam olarak gerçeklenmesi mümkün olmayan ve/veya pahalı olan oşinografik incelemeler için gelecek vaat eden araçlardır.

SDA mimarisi uygulamaya bağlı olarak değişir. Sözgelimi, petrol çıkartma tesislerinin görüntülenmesi veya deniz saha güvenliği sabitlenmiş duyarga düğümleri olan bir SDA'ya gereksinim duyarken, kimyasal sızıntı tespiti, sabit olmayan, serbestçe yüzen duyarga düğümlerden oluşan gezgin bir SDA'ya gereksinim duymaktadır. SDA, otonom sualtı araçları, otonom yüzey araçları, yönetilen sualtı araçları, planörler ve sualtı robotları gibi duyargalar ve gezgin cihazları içeren melez bir mimariye de sahip olabilir. Bu değişik uygulamalar ve mimariler, SDA'ların işlerliği için gerekli olan protokolleri tanımlamaktadırlar. Ancak yine de, bir duyarga ağın en temel ihtiyaçlarından biri konumlandırmadır.

Konumlandırma temel olarak, bir düğümün enlem, boylam, yükseklik veya diğer düğümlere göre nerede bulunduğu bilgisidir. Konum bilgisi veri etiketleme, hedef belirleme ve düğüm izi sürme için temel bir gereksinimdir. Veri toplama ve etiketleme dışında, bir duyarga ağın, toplanan veriyi merkez bir istasyona göndermesi de gerekmektedir. Dahası, yeni uygulamalar, düğümlerin koordineli bir görevi yerine getirmek için haberleşmelerini gerekli kılmaktadır. Bu nedenle, veri gönderimi ve ortam erişimi diğer önemli konular olarak belirmektedir. Uygulamaya bağlı olarak, uçtan uca güvenli veri gönderilmesi de önemli olabilir. Karasal duyarga ağlarda konumlandırma, ortam erişimi ve veri gönderimi yeterince fazla çalışılmıştır. Ancak, karasal duyarga ağlarındaki teknikler, çoğunlukla sualtı haberleşmesindeki zorluklardan dolayı SDA'lar için etkin yöntemler değildir.

Sualtı ağının gerçeklenmesi akustik haberleşme ile mümkündür. Akustik kanal düşük bandgenişliğine, düşük bandgenişliğinden kaynaklanan düşük veri hızına, yüksek yayınım gecikmesine, yüksek bit hata oranına sahiptir. Ayrıca akustik işaretler zamanla değişen özelliklerle birlikte kırılarak farklı yolladan varışa ulaşma sorunuyla karşılaşabilirler. Şu anda, kısa mesafeli akustik sualtı modemleri saniyede 20-50 kbit'lik veri hızına ulaşabilmektedirler. Sesin hızı saniyede 1500m olmakla birlikte, sıcaklık, tuzluluk ve yoğunluk gibi dinamik okyanus özelliklerine bağlı değişim gösterir. Yüzeyden veya okyanus dibinden yansımalar, işaretin kırılarak farklı yollara sapmasından kaynaklı yayınıma neden olur. Dahası, yüzey dalgalarının yer değiştirmesi de zamanla değişen yayınım özelliklerine neden olur.

Akustik haberleşme, fiziksel katmanda gürbüz işaret işleme tekniklerine gereksinim duyar. Diğer yandan, yüksek yayınım gecikmesi, kısıtlı bandgenişliği, enerji tasarrufu

üst katmanların tasarımını etkiler. Hareket, SDA'nın doğal bir özelliğidir ve SDA protokollerinin tasarımını etkilemektedir.

Literatürde SDA'larda veri toplama, senkronizasyon, konumlandırma, yol atama ve ortam erişimi üzerine odaklanan çalışmalar bulunmaktadır. Bu çalışmaların çoğu benzetim temellidir, çünkü bu çalışmalar için fiziksel olarak SDA'ların kurulumu ve çalıştırılmasının maliyeti yüksektir.

Bu tezde, SDA'larda konumlandırma ve veri dağıtımı üzerinde yoğunlaşılmaktadır. Karasal duyarga ağları için konumlandırma çözümleri bulunsa da, bu sorun SDA'larda birçok nedenden ötürü zorlaşmaktadır. Öncelikle, okyanusta su yüzeyi altında GPS kullanılamamaktadır. Ayrıca, varolan GPS kullanmadan konumlandırma teknikleri, çok sayıda paket değişimini gerektirmektedir ki buna SDA'ların kısıtlı pil gücünün yetmesi zordur. Sıkı enerji kısıtları da minimum protokol ek yükünü gerektirmektedir. Dahası, gezginlik durumunda konumlandırmanın periyodik olarak tekrarlanması gerekmektedir.

Bu tezde, iki konumlandırma algoritması önermekte ve önerdiğimiz bu algoritmaların başarımını, litratürde var olan bir teknikle karşılaştırmaktayız. Önerdiğimiz algoritmalar İner-Çıkar düğümlerle Konumlandırma (İÇK) ve Vekil Konumlandırma (VK) yöntemleridir. İÇK, hacim genleştirme tekniğiyle su içinde düşey düzlemde inme ve çıkma özelliğine sahip özel düğümler kullanır. İÇK çapaları koordinatlarını, okyanus yüzeyinde yüzerken GPS aracılığıyla öğrenirler ve inip çıkarken kendi koordinatlarını diğer düğümlere duyururlar. Bir sualtı düğümü, İÇK'nin koordinatlarını ve laterasyon yöntemini kullanarak kendi koordinatlarını kestirir. VK, İÇK'ye iteratif bir yaklaşım ekler ve başarılı bir şekilde konumlandırılmış olan sualtı düğümlerinin, kendilerinin bir sekme uzağındaki konumlandırılmamış komşuları için konum vekili olmalarını sağlar. İÇK ve VK'nin başarımlarını Geniş Ölçekli Konumlandırma (GÖK) metodu ile karşılaştırmaktayız. İÇK ve VK'nin GÖK ile karşılaştırılma nedeni, bu protokollerin benzer SDA mimarileri için konumlandırma sorununu çözüyor olmalarından kaynaklanmaktadır. Bu protokollerin tümü dağıtık ve geniş ölçekli, gezgin SDA'lar için uygulanabilirdir. GÖK üç tip düğüm kullanmaktadır. Yüzey düğümleri, su yüzeyinde yüzerler ve periyodik olarak GPS'den elde edilen koordinat bilgilerini çapa düğümlere gönderirler. Çapa düğümler sualtında yüzerler ve normal düğümler arasına farklı derinliklerde yayılmışlardır. Çapa düğümler, koordinatlarını *beacon* adı verilen sinyallerle bir sekme komşulukta, uzak emsafede bulunan düğümlerden öğrenirler. Sonrasında, çapa düğümler kendi koordinatlarını komşularına periyodik olarak duyururlar. GÖK yönteminde, normal düğümler, kendilerine bir veya iki sekme komşuluktaki çapa düğümlerin koordinatlarını kullanarak laterasyon yöntemiyle öğrenirler. Bu tezde, İÇK, VK ve GÖK'ün başarımını konumlandırma başarısı, doğruluk, ek yük, enerji tüketimi ve gecikme parametreleri açısından karşılaştırmaktayız. Başarım karşılaştırması içinse, akustik fiziksel katmanın bulunduğu Qualnet benzetim ortamını kullanmaktayız.

Durağan ve gezgin SDA üzerinde çalıştığımız için, gerçekçi bir gezginlik modeli en temel gereksinimlerden biridir. Okyanuslarda serbest yüzen nesneler akıntıların gücüyle hareket ederler. Biz yaptığımız çalışmada, yüzey katmanı gezginlik modeline ek olarak alt-yüzey akıntılarını modelleyen Salınan Gezginlik Modeli'ni (SGM) temel almaktayız. Yüzey Etkisini hesaba katan SGM'yi kullanarak İÇK, VK ve GÖK'ün başarımı gezgin bir senaryoda karşılaştırılmaktadır.

Tezde ayrıca SDA'da veri dağıtımını da incelemekteyiz. Konum tabanlı yol atama protokolünün başarımını değerlendirmekteyiz. Tezin ilk bölümlerinde konumlandırma yaklaşımlarımızı önerdiğimiz için, veri dağıtımı için konum tabanlı yol atamanın düşünülmesi doğaldır. Analize, konum tabanlı yol atama protokolü ile reaktif topoloji tabanlı yol atama protokolünün başarım karşılaştırması ile başlamaktayız. Açgözlü bir konum tabanlı yol atama protokolünü gerçeklemekte ve AODV (Ad hoc On-demand Distance Vector - Tasarsız isteğe bağlı uzaklık vektörü) protokolünü de reaktif topoloji tabanlı yol atama protokolü olarak kullanmaktayız. Konum tabanlı protokolün başarımını konumlandırma doğruluklarındaki hatalar altında test etmekteyiz. Konumlandırma protokolleri doğal olarak kestirim hataları ile çalışırlar bu nedenle bu durum, konum tabanlı protokolün veri dağıtımı başarımında olumsuz etkiye neden olmaktadır.

Sonuç olarak tezin bütününde, İÇK ve VK adlı iki dağıtık, geniş ölçekli esnek konumlandırma tekniği önermekteyiz. Bu tekniklerin konumlandırma başarısını, doğruluğunu, ek yükünü, enerji etkinliğini ve gecikmesini, literatürde bulunan GÖK adlı teknikle karşılaştırmaktayız. Sonuçlar İÇK'nin gezgin senaryolarda diğer yöntemlerden çok daha iyi sonuç verdiğini göstermektedir. Statik senaryolarda ise İÇK enerji etkinliği açısından avantajlıyken, GÖK yüksek veri dağıtım oranından dolayı tercih edilebilirdir. İnce taneli konumlandırma protokollerinin veri dağıtımı üzerinde oldukça hafif bir etkisi vardır. Bunun nedeni, ortalama hata oranlarının göreli düşük olmasıdır. Eğer iri taneli konumlandırma yöntemleri kullanılırsa ortalama hata oranı artar ve düşük kesinlik değerleri veri dağıtım oranının düşmesine yol açar.

1. INTRODUCTION

Underwater Sensor Networks (USN) are used for harsh oceanographic missions where human operation is dangerous or impossible. USNs can improve the current naval defense, earthquake/tsunami forewarning, water pollution detection, mine reconnaissance missions and ocean life monitoring systems. Besides, they enable new opportunities for securing oil drilling sites and surveillance for critical regions in underwater. Stationary USNs are ideal for securing or monitoring a fixed target region. For example, a mine reconnaissance application that uses underwater robots in mine-hunting, requires a short-term, stationary network. On the other hand, mobile (untethered [1]) USNs are more suitable for dynamic missions. For example, consider a USN where a group of underwater sensor nodes are responsible for monitoring a region for a chemical attack. If the enemy launches an attack through the waters, the chemical spill can be followed by untethered underwater sensors. USNs are in their infancy and they present numerous challenges for the networking community.

Localization is one of the major tasks in a sensor network. Location of a sensor node is essential for data tagging, target detection and node tracking. After collecting the intended data, a sensor network needs a mechanism to deliver the data to a central station or the sensor nodes may need communication to work cooperatively. Therefore, data-delivery is another important task. Communication among the nodes that share the same medium necessitates medium access techniques and this again is an important issue. Depending on the application, reliable end-to-end delivery can become significant, as well. Localization, medium access, data delivery are well studied topics in terrestrial sensor networks. However, the techniques in terrestrial sensor networks become inefficient for USNs due to the challenges of underwater communication.

[1] Hereafter we will use “mobile” and “untethered” interchangeably to mention the sensor nodes that are not anchored and can drift with the force of the currents.

In underwater networking, acoustic communication appears to be a better alternative to optical or radio communication. High frequency radio waves attenuate and optical communication can be used in clear water and short range. Currently, acoustic is foreseen to be the enabling technology. Nevertheless, the physical channel conditions are a lot rougher than those of terrestrial radio or acoustic channel in air. Underwater acoustic wireless communications have bit rates around 20-50 kbit/s which is very low compared to Radio Frequency (RF) communication. The speed of sound is low. It is approximately 1500m/s and this may vary due to temperature, salinity and density variations in different parts of the ocean [1]. Due to low speed of the signal, the propagation delay is large. It is five orders of magnitude higher than RF communications. The Bit Error Rate (BER) is also high. In [2] BER is given as 10^{-2}. Although new acoustic modems report lower BER, the error rates are still higher than RF communication. The acoustic signals have multipath propagation and their characteristics vary in time. Multipath propagation is due to surface-bottom reflection and refraction of sound in water. Time variability is mostly the result of the surface waves.

The challenges of acoustic communications demand robust signal processing techniques and they need to be addressed at the physical layer. On the other hand, large propagation delay, limited bandwidth and energy efficiency can be handled at the upper layers. Besides the challenges stated above, motion is an inherent property of the USN and it affects the operation of the network. In the literature, there are previous works that focus on data gathering, synchronization, localization, routing and medium access issues for USNs. Since USNs are in their infancy and deploying a USN is costly, there are very rare works established on a test bed. Generally, the algorithms are analyzed using simulations.

In this thesis, we focus on two issues: localization and data delivery. Localization is a well studied topic in terrestrial sensor networks. However, in USNs, localization is more challenging than its terrestrial counterpart. There are several reasons for that. GPS can only be used by the surface nodes because GPS signal does not propagate well through the water. GPS-less positioning schemes depend on heavy communication among nodes. The low bandwidth, high propagation delay and high bit error rate of the acoustic channel restricts protocol overhead. GPS-less schemes have to be reconsidered to work with less overhead. Decreasing the overhead is also enforced by the limited battery life of the nodes and the difficulty of recharging or replacing batteries in an underwater application. Moreover, a Mobile Underwater Sensor Network (MUSN) requires periodic localization process.

In this thesis, we propose two localization algorithms and compare their performance with a recognized technique from the literature. Our proposals are Dive aNd Rise Localization (DNRL) and Proxy Localization (PL). The Dive and Rise (DNR) localization is proposed in [3]. The DNR Localization (DNRL) uses several special nodes that are able to ascent and descent in the water column by using a volume expansion technique. The DNR beacons learn their coordinates from GPS while they are floating on the surface of the ocean. Then, they descent until they reach the maximum depth of the USN. After that, the DNR beacons ascent to receive GPS coordinates. During this dive and rise period, DNR beacons announce their coordinates at several intervals. An underwater node can be localized if it hears localization messages from at least three DNR beacons. Proxy Localization (PL) [4], adds an iterative approach to DNRL and enables the successfully localized underwater nodes to become location proxies for their non-localized one hop neighbors. We compare the performance of DNRL and PL with the localization method proposed by Cui et al [5]. We call this scheme as the Large-Scale Localization (LSL) method. LSL has an hierarchical architecture where there are three types of nodes. “Surface buoys” float on the surface and periodically send the GPS driven coordinates to “anchor nodes”. Anchor nodes float in underwater and they are scattered among the “ordinary nodes” at several depths. Anchor nodes learn their coordinates from surface buoys via one hop, long-distance links. Then, they periodically broadcast self coordinates to their neighbors. In the LSL method, ordinary nodes are localized by lateration, using the coordinates of anchor nodes which are one or two hops away. We compare the performance of DNRL, PL and LSL in terms of localization success, accuracy, overhead, energy consumption and delay. We use the Qualnet simulator with an acoustic physical layer.

The reason for comparing DNRL and PL to LSL is that they aim to solve the localization problem for similar USN architectures. They are all distributed and suitable for large-scale mobile USNs. Since we consider mobile USNs, a realistic mobility model is essential for a comprehensive analysis. The so-called random waypoint mobility model is not suitable for modelling the mobility pattern in the oceans. In aquatic environments, free-floating objects move by the force of the currents. Currents are the result of a complicated interaction between temperature, pressure differences and winds. We collaborated on a mobility model, Meandering Current Mobility with Surface Effects (MCM-SE) [4]. The MCM model is an established model in oceanography which models the Gulf stream currents. These currents affect the motion in several hundred meters below the surface. The MCM-SE model adds a surface layer to MCM. We use MCM-SE to evaluate the performance of DNRL, PL and LSL under a mobile scenario.

In this thesis, we also study data delivery in underwater sensor networks. In a USN, the data delivery scheme and its performance depend on the application scenario. We focus on a mine reconnaissance application where the sensor nodes monitor a coastal region and periodically report data. For this scenario, we investigate the performance of a location-based routing protocol. Since we propose localization schemes in the previous sections, it is natural to consider location-based routing for data delivery. We start our analysis by comparing the performance of a location-based routing protocol to a reactive topology-based routing protocol. We implement a greedy location-based protocol and use Ad hoc On-demand Distance Vector (AODV) as the reactive topology-based routing protocol. Greedy location-based routing selects the neighbor with the minimum geographic distance to the destination as the next hop. If a node cannot find a next hop in the greedy phase, the packet is dropped. This means a packet is dropped if it meets a geographic void. The topology-based routing protocol uses the connectivity information and selects the neighbor with the minimum hop distance to destination as the next hop. The packet is dropped if the graph is disconnected.

Besides comparing a location-based and a topology-based protocol, we analyze the performance of the location-based protocol under localization inaccuracies. Localization protocols naturally have an estimation error and this may have a negative impact on the delivery success of the location-based protocol. We investigate the interaction of the localization protocols and location-based routing. The localization protocols used in this thesis have low error in stationary USNs however, course grained localization methods may introduce higher error. In order to show the impact of estimation error on the performance of the location-based routing protocol, we artificially introduce high mean error on location estimates. Location inaccuracy adversely affects the delivery ratio of location-based routing protocol as expected.

The rest of the thesis is organized as follows:

- Chapter 2 introduces the localization problem, describes the basic techniques of range measurement and summarizes the localization techniques proposed for terrestrial sensor networks. After presenting the state-of-the-art of the oceanographic systems and the challenges of underwater networking, this chapter continues with a detailed survey on localization proposals for USNs. Chapter 2, also summarizes related works on data delivery schemes.

- Chapter 3 explains the mobility model used for simulating the mobile USN. MCM model is an established model of subsurface currents in oceanography. Surface motion is included in MCM-SE model which is explained in this chapter.

- Chapter 4 gives the detailed description of the localization techniques developed in the scope of this thesis study, i.e. DNRL and PL. This chapter also describes the LSL scheme which is a localization technique from the literature that works in a similar underwater architecture to our techniques. The architecture description, packet exchange mechanisms and localization table update algorithms of DNRL, PL and LSL are given in this chapter.

- Chapter 5 presents the simulation results for DNRL, PL and LSL for a mobile USN. The simulation results are given in terms of localization success, accuracy, overhead, energy consumption and delay. Performance evaluation under a stationary network is presented in appendix A.

- Chapter 6 investigates data delivery in an underwater sensor network considering a specific application, i.e., underwater mine reconnaissance. This chapter compares the performance of a topology-based and location-based routing protocol. Chapter 6, analyzes the impact of the accuracy level of the localization schemes to the location-based routing. This chapter also investigates the performance of the location-based protocol under poor accuracy.

- Chapter 7 concludes the thesis and draws future directions.

2. RELATED WORK

Exploring the oceans has been of interest to navy forces for several decades and it has gained popularity within the last five years. Recently, Robert Headrick from the Office of Naval Research (ONR), indicates in an IEEE Communications Magazine article [6] that the US Navy has an expanding interest in underwater networks. The ONR is currently funding several projects on underwater networks. Their growing interest motivated researchers working in the communications field and underwater sensor networks has become an active research field in the 2000s.

In underwater sensor networks, the challenges of the physical medium necessitate novel solutions or the re-design of known protocols for the medium access, routing, transport and localization tasks. In this thesis, we propose localization techniques and analyze data delivery, therefore, the related work is limited to general challenges, localization and data delivery. Localization techniques for the USNs may be influenced by the terrestrial sensor localization techniques. Thus, in the following sections, we first give a brief summary of localization basics and localization for terrestrial sensor networks. Next, we describe the localization solutions for the currently used systems in oceanography. Although current oceanographic monitoring systems are generally composed of independent devices that do not communicate, ocean floats can be considered as the ancestors of the underwater sensor nodes. We also give a short introduction to the challenges of underwater acoustic communication in order to familiarize the reader to the complications of the physical medium and its effects on localization protocols and data delivery. In the last sections, we give a detailed survey of recent localization schemes and data delivery approaches for USNs.

2.1 Localization Basics

Localization, basically means estimating the location of a node. Location can either be a global (latitude, longitude, altitude) or a local (position information relative to other nodes in a local coordinate system) information. The majority of the underwater sensor network applications require global location information. Localization process consists of two steps. The first step is collecting information about the neighbor nodes (e.g. distance to neighbors/anchors, angle between neighbours/anchors, connectivity information) and the second step is applying this information to a triangulation algorithm. Triangulation is a general term which means using the geometric properties of triangles for localization. It is divided into two categories; namely, lateration and angulation [7]. Lateration calculates the location of an object by using distance measurements. These distance measurement which are usually referred to as ranges. The angulation method uses bearing. Bearing is the angle with respect to another object. Whether lateration or angulation is used, distance or angle between the object and its neighbors should be determined. These quantities can be measured via several methods: *i*) Received Signal Strength Indicator (RSSI), *ii*) Angle-of-Arrival (AoA), *iii*) Time Difference of Arrival (TDoA), *iv*) Time of Arrival (ToA) [8].

RSSI measures the signal power at the received end and calculates the propagation loss as the difference between the transmitted and the received power. Then, this propagation loss is transformed into a distance estimate via theoretical or empirical models. RSSI is not reliable in underwater because the effects of coastal/ship/tide noise and the complicated multipath effects caused by reflections form ocean bottom and surface are not yet fully modeled [9].

AoA technique uses geometrical methods to derive the positions of the nodes and needs directional receivers/transceivers. AoA may be applicable to USNs where the underwater sensor nodes are large enough to host directional antennas unlike the terrestrial sensor nodes [10]. In practice, directional antennas are avoided due to extra-cost.

TDoA uses the time difference between the RF signal and the acoustic/ultrasound signal to calculate propagation delay. However, RF signal cannot be used underwater.

ToA method uses the one-way propagation time and the speed of the signal to calculate the distance. In terrestrial systems, the time of arrival for light or radio signal acquires high resolution timers. For instance, it takes approximately 33 nanoseconds for a light pulse to travel 10m. The speed of sound in air is six orders of magnitude lower than that of light (approximately 344m/s at 21^{o}C). In this case, it takes 29 milliseconds for a sound wave to travel 10m. Since the speed of sound is also low in water, ToA can be used in ranging for USNs. ToA is the most cost effective method when the nodes are synchronized. However, if the nodes are not synchronized, round trip time may still give an approximate value for the distance. Unfortunately, in underwater, clock skew and the lack of speed profile of sound, may degrade the performance of ToA-based methods.

RSSI, AoA, TDoA and ToA are the ranging methods that provide distance estimates for the range based localization algorithms.

2.2 Localization in Terrestrial Sensor Networks

Up-to-date terrestrial localization schemes can be classified as range-based and range-free schemes. Range-based schemes are the simplest solutions for absolute localization. If there are anchor nodes, i.e. nodes with pre-known location, a multilateration algorithm is applied to the estimated ranges and the coordinates of anchor nodes.

When none of the nodes have their location information, anchor-free, range-based techniques can be considered [11, 12]. These schemes generally establish cooperative localization by using the relative position information of the neighbors and form a coordinate system spanning the whole network. They usually include initial range-measurement, location estimation and refinement phases [13]. To match the relative coordinate systems and achieve a global view of the network, the refinement phase is essential. Anchor-free techniques require a large amount of messaging therefore they are not suitable for USNs.

There are also range-free localization techniques for terrestrial sensor networks. Range-free techniques use the connectivity information among the nodes and they do not measure the distance explicitly [14, 15]. An example of a range-free technique, namely, the centroid method [16] uses fixed anchor nodes at the intersection points of the grid. The coordinates of a non-localized node is estimated as the average of the several beacon coordinates. This scheme has high deployment cost and is not feasible for USNs. Especially, for mobile USNs it is not possible to set up an infrastructure at a fixed position and then perform localization for moving/drifting nodes. In [17], the product of the average hop distance and the hop count is used to estimate the actual distance between the non-localized node and the anchor. In this scheme, nodes learn the hop count by flooding which increases the messaging cost and energy consumption. For the mobile USN, since the localization procedure has to be repeated periodically the overhead for the range-free localization protocol would be high. Therefore this is not feasible for USNs, as well.

Global Positioning System (GPS) is a well-known anchor and range-based technique. However, it can only be used outdoors. In order to achieve positioning via GPS the receiver should have line-of-sight communication with four satellites. In aquatic networks, GPS can be used only by the surface nodes because the high frequency GPS signal does not propagate through the water and cannot reach the underwater nodes. Alternatives to GPS have been investigated for indoor terrestrial applications and for sensor networks where GPS receiver is unaffordable [11, 12].

Localization is more challenging for mobile networks than for stationary networks. In stationary underwater sensor networks, localization can be done with little effort by launching the nodes in predefined locations. For tethered architectures, if the sensors are anchored to the ocean bottom they are placed in a predefined location or if the surface buoys are used the tethered nodes can get their coordinates through GPS via a receiver above the surface.

Localization for *mobile* terrestrial sensor networks is rarely studied [18, 19]. Adaptive and prediction-based schemes are proposed and their performance is compared in [18]. The adaptive scheme adjusts the localization frequency according to the motion of the sensors. The sensors reduce their localization frequency when they move slowly, and increase when they move fast. Prediction-based localization uses dead-reckoning to compute the mobility pattern. Sensors estimate their motion pattern and use this to predict their location in the future. This study shows that the mobility pattern information is critical for the analysis of prediction based systems. If the mobility lends itself to prediction, that is there is spatial correlation, the success of the prediction increases. In random motion, prediction does not help much, as expected.

Positioning and localization have also been extensively studied in the context of mobile robot navigation. However, image processing and visually recognizable landmarks have generally been used in robotics. Sequential Monte-Carlo localization, a robot localization technique, is applied to a mobile sensor network in [19]. This method also relies on the landmark idea. Nodes measure the distance between the nodes and several mobile seeds. These observations are used to filter out the unlikely location estimates.

2.3 State-of-the-art in Oceanographic Systems

For several decades, oceanographers have been developing data collection equipments to explore oceans. These equipments are either Eulerian or Lagrangian devices. The former are stationary while the latter can passively follow the ocean currents. Especially, Lagrangian devices give unique insights to the structure and patterns of the ocean flows. “Drifters” and “floats” are two such Lagrangian devices. “Drifters” float on the surface of the ocean and “floats” float several kilometers below the surface. There are also profiling floats which can move vertically in the water column and collect data from varying depths.

The first trackable subsurface floats were Sound Fixing And Ranging (SOFAR) floats designed by Woods Hole Oceanographic Institute in 1955 [20]. The SOFAR floats were equipped with sound sources and they could be tracked by an attendant ship. In 1980s, sound sources were moved from the floats to moorings. Those floats were called RAFOS (SOFAR spelled backwards). RAFOS floats have been used in USA, France and Germany for ocean/sea monitoring. The main purpose of these floats were collecting information on temperature, salinity and pressure by following ocean currents. The collected data were stored on-board and transmitted to the satellite when the floats surfaced at the end of their mission which lasted months to years. RAFOS floats could listen to sound sources on moorings and then triangulate to localize themselves. By this way, floats could consume less energy than sending acoustic signals themselves. These two approaches used in SOFAR and RAFOS are the examples of the two widely used localization techniques in aquatic environments: Short and Long Base-Line (SBL and LBL) systems, respectively [21]. In SBL and

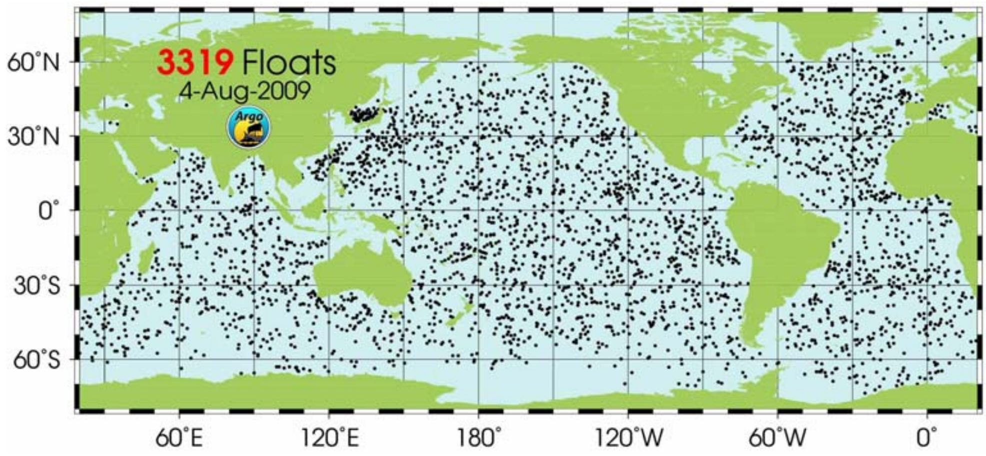

Figure 2.1: Recent status of the Argo floats (Argo project web site, August 2009).

LBL, the positions of sensors are determined on the basis of acoustic communications with a set of receivers. In the SBL system, a ship follows the underwater devices and uses a short-range emitter to enable localization. In the LBL system, acoustic transponders are deployed either on the seafloor or under the surface moorings around the area of operation. The devices that are in the transmission ranges of several sound sources are able to estimate their location.

A more recent and the largest ocean monitoring system is conducted by the Argo Project. Argo is a global array of free-drifting profiling floats that measure the temperature and salinity of the upper 2000m of the ocean. Deployments of Argo floats began in 2000 and by December 2008, more than 3000 Argo floats have been launched successfully [22, 23] (see Figure 2.1 for the recent status of Argo floats).

An Argo float is composed of three subsystems: hydraulics system that control buoyancy adjustment via an inflatable external bladder to enable ascending and descending, microprocessors to control and schedule routine tasks and data transmission system that controls communication with the satellite. The approximate weight of an Argo float is 25kg and an illustration is given in Figure 2.2. A usual life cycle of an Argo float is to descend to 1000m depth from the surface by using volume expansion technique, drift with the current for 10 days then descent to 2000m within two hours and then ascend to surface and stay on the surface for 10 hours to transmit data to the satellites. SOFAR, RAFOS and Argo floats were all designed to transmit their data to the satellite in a non-real time fashion. When these devises were built, communication among them was not considered. The communication

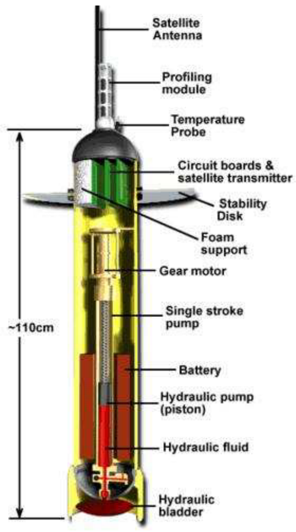

Figure 2.2: An illustration of an Argo float (Argo project web site, August 2009).

capability among nodes enables the "underwater network". In an underwater network the data collected by the sensors can be relayed to a central station over multi-hop links. Although networking these Lagrangian devices have been very appealing for the oceanographic research [24], only recently, a prototype float that can communicate with its peers, has been designed [25].

Besides the demand for wireless communication of the floating devices, there are also recent efforts to set up a wired network in the ocean floor. NEPTUNE [26], VENUS, MARS and JAMSTEC observatories are the examples of such ocean floor networks. NEPTUNE (North East Pacific Time-integrated Undersea Networked Experiments) is a cabled regional underwater network in northeast Pacific. The installation of the first stage in Canadian waters has been completed recently and the second stage in US is foreseen to be operational in 2013. A conceptual drawing of NEPTUNE network is given in Figure 2.3. Stage 1 lays an 800 km ring of powered fiber optic cable on the seabed covering a 200,000 km^2 region. The underwater network is planned to have five or six ocean floor "laboratories" which are named as nodes. These nodes will provide a remote test environment for the land-based scientists. Scientists will work via interactive instruments to explore events such as storms, plankton blooms, fish migrations, earthquakes, tsunami, and underwater volcanic eruptions, as they happen. The NEPTUNE benefits from the installation of two test networks in 2006-07: the VENUS (Victoria Experimental Network Under the Sea) and the MARS (Monterey Accelerated Research System) projects [27] which are small scale observatories similar

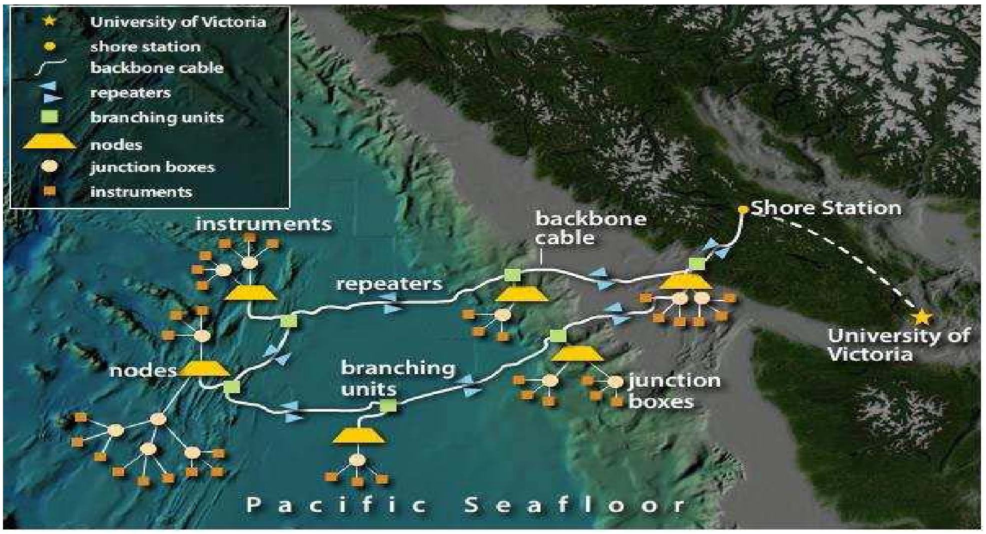

Figure 2.3: An illustration of NEPTUNE network at British Colombia bay (Neptune project web site, August 2009).

to NEPTUNE. Moreover, Japan Agency for Marine-Earth Science and Technology (JAMSTEC) operates three cabled observatories in the northwest Pacific around Japan [28] which are used for biological life monitoring as well as seismic research. In these networks, the employed wired fixed nodes and cabled mobile nodes will not need complex localization methods. However, if a hybrid network contains untethered devices, localization of those devices will be an issue. Since these networks are considered for fixed nodes, to the best of our knowledge, localization has not been studied for the ocean floor wired networks.

In fact, the underwater network can have a hybrid architecture to include various devices, such as cabled stationary systems, passively floating devices, autonomous vehicles, remotely operated devices and robots. Remotely operated underwater vehicles (ROV), Autonomous Underwater Vehicles (AUV), Autonomous Surface Vehicles (ASV), Supervised Underwater Vehicles (SUV) and gliders are among the developing underwater equipments. They can also have on-board sensors and antennas. Their communication capability will enable a hybrid underwater sensor network.

Seaweb is the first effort to include AUVs, gliders, buoys, repeaters and ships in a hybrid architecture. Seaweb is the US Navy undersea wireless network [29]. An illustration of Seaweb is given in Figure 2.4. It has been under development since 1998. In Seaweb, the devices can communicate via telesonar, radio or satellite links. Telesonar links are used to communicate in underwater and radio links are used to

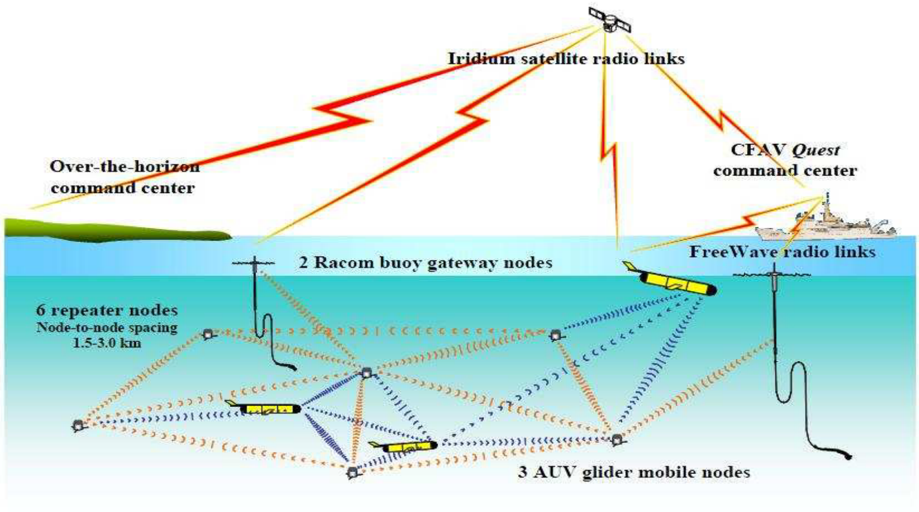

Figure 2.4: Seaweb network in the Eastern Gulf of Mexico on February 2003, including three AUVs, six repeater nodes, and two gateway buoys (Rice, 2007).

communicate with the command center on the ship. The on-shore command center is accessed via satellite links. Localization and navigation underwater uses telesonar signals.

2.4 Challenges of Underwater Acoustic Communication

For the aquatic network, current wireless communication techniques are satellite, radio, Cellular Digital Packet Data (CDPD) or acoustic. In fact, when the devices do not surface, the only feasible communication is acoustic communication. Radio waves propagate through conductive salty water only at low frequencies such as 30-300Hz [30]. Since they do not propagate well in underwater, satellite, radio and CDPD cannot be used for data transmission below the surface level.

Longwave radio and optical signaling are analyzed in [31] as possible alternatives to acoustics. Long-wave radio is observed to have data rates of 1-8kbit/s at 122kHz carrier frequency, at ranges 6-10m. Another disadvantage of longwave radio technology is that it requires high power and large antennas. On the other hand, optical signals do not suffer from attenuation as much as radio signals but they are scattered. The observations in [31] show that blue-green waves can be used only in very clear water with data rates reaching Mbit/s at ranges up to 100m.

For medium range and ordinary water clarity acoustic seems to be the best alternative. Nevertheless, acoustic propagation is also challenged from several aspects which are mainly; attenuation at high frequencies, time-varying multipath propagation and low speed of sound [32]. For acoustic signals, it is reported that the frequency upper bound is 1Mhz for 60 meters of range [33]. Hence underwater communications is viable through low-frequency acoustic signals. Inherently, acoustic wireless communications is expected to have low bit rate, such as 20-50 kbit/s. In addition to the limited bandwidth, the speed of sound is low which introduces large propagation delay. The propagation delay is five orders of magnitude higher than in Radio Frequency (RF) communications. The speed of sound is approximately 1500m/s, it may vary due to temperature, salinity and density variations in different parts of the ocean [1]. Bit Error Rate (BER) is also high. In [2] BER is given as 10^{-2}, although new acoustic modems report less BER. Multipath propagation is due surface-bottom reflection and sound refraction in water. Time variability is mostly the result of surface waves which cause the displacement of the reflection point [32] Besides the challenges stated above, motion is an inherent property of USNs. When either mobile platforms such as AUVs or passively moving equipments such as drifters are used, the nodes of a USN could be subject to displacement on the order of few meters per second. In the case where either the transmitter or the receiver is in motion the Doppler effect may be observed. The magnitude of the Doppler effect is related with the ratio of the relative transmitter-receiver velocity to the speed of the signal. Since the speed of sound in water is low when compared to the speed of electromagnetic waves, the Doppler effect is strongly effective in acoustic communications.

In underwater sensor networks the energy constraints of the sensors appears as another problem. Without sustainable energy source and energy-aware MAC protocols the lifetime of a USN will be shorter. Higher layer protocols need to be energy-efficient as well.

In summary, the challenges of underwater sensor networking are the following:

- Long propagation delay
- Limited bandwidth
- Impaired physical channel due to multipath and fading

- Low link quality due to high error rates and temporary loss of connectivity
- Limited battery life
- Frequent node failures due to fouling and corrosion

Most of these challenges that are related with acoustic communication are addressed at the physical layer. Acoustic modems are designed to work in these conditions. Some of the well-known acoustic modems are WHOI modem [34], Aquacomm [35], Linkquest [36] and Teledyne Benthos telesonar modem [37]. In [38], a comparison between the WHOI modem and Aquacomm has been presented. The WHOI modem has a data rate of 220 bits/sec over 5000 m at 10W transmission mode. The Aquacomm modem [35] has a data rate of 480bit/s over 200m at 0.45W. It spends 4.5mJ/bit. The Linkquest modem has 38Kbit/s over 1000m range and it has 6W transmit mode power consumption.

At upper layers, large propagation delay, limited bandwidth, energy efficiency, temporary loss of connectivity need to be addressed [39]. All applications, transport, network, medium access protocols, synchronization and localization protocols are affected by these hard physical conditions.

There are previous works that have focused on data gathering [38], synchronization [2], localization [13], routing protocols [10, 40], energy minimization and medium access [41] issues. These works generally include simulation studies. Real world implementations of underwater acoustic multi-hop sensor networks are limited where only premature test results, mostly due to device failures, are reported [42, 43].

2.5 Recent Localization Schemes for Underwater Sensor Networks

In [13], a survey of the localization algorithms developed for terrestrial sensor networks is given and their applicability to USNs is investigated. In this section, we give a comprehensive literature survey of underwater localization solutions.

The conventional Long Baseline (LBL) and Short Baseline (SBL) systems which have been used in oceanographic research for several decades are not suitable for the USNs. In SBL a mobile platform, usually a ship, follows the underwater equipments and provides beacons in short range. SBL has high cost and is not feasible for the USN since a ship cannot follow a large scale sensor network. LBL uses high power signals sent by the moorings that are kilometers apart. LBL is not feasible because these ping signals create interference and disable the communication among the sensor nodes. Alternative solutions have been recently investigated for underwater sensor networks.

The GPS Intelligent Buoy(GIB) system is a commercial system that works as underwater GPS for AUVs, divers and other underwater equipments. The underwater equipment emits acoustic signals. The surface buoys listen to these signals and estimate the distance via ToA. These distance measurements are sent to a central station where the location of the underwater equipment or diver is determined. This centralized system is useful for node tracking however, the USN is expected to collect and tag data. In this case, determining the location at a centralized control center is not suitable, hence distributed localization schemes are better alternatives.

There are a few recent distributed localization schemes for USNs that aim to have low cost, work in the 3-D space and handle mobility. A distributed localization scheme for a mobile underwater sensor network is proposed in [3]. Beacon nodes receive GPS coordinates while floating at the surface. They periodically dive and rise to act as the underwater GPS. Dive'N'Rise (DNR) beacons periodically descend and ascend using the same principle of profiling floats and in the meanwhile they broadcast their coordinates. In DNR Localization (DNRL), the sensor nodes are able to learn their coordinates just by listening. This passive listening results in energy saving and reduces the communication cost. Moreover, mobile beacons increase the localization coverage in 3D space. DNR beacons move with the other nodes in the USN, hence the localization scheme works well with the mobile nodes. The details of this method is given in Chapter 4. In [3], a simple mobility model is considered. A more realistic mobility model is required to model the complex behaviour of the ocean currents.

In [5], the authors consider a hierarchical localization technique for stationary large-scale USNs. A detailed description of this technique is given in Chapter 4.

In [44] the authors, propose an anchor-free, cooperative localization method for USNs. A seed node is assumed to have its location information. This seed node sends a broadcast message to its neighbors and collects the distance estimates. Then it selects the furthest node it can communicate as the second seed. This new seed sends a broadcast message to select a third node. These three nodes are able to localize the nodes at their intersection area (the first seed being the origin and the second and third defining the x and y axis.) For localizing all the nodes in the network, new seed nodes are selected in the same way. This process is called as node discovery. Clearly, node discovery phase requires high number of messaging. These kind of protocols may be used for stationary USNs where localization only runs in the initialization of the network. For mobile sensor networks, repeating the node discovery each time the topology changes is unaffordable.

The Area-based Localization Scheme (ALS) for underwater sensor networks, is proposed in [45]. ALS is a range-free, centralized, course-grained localization technique. It can be used where accurate location information is not necessary and when the anchors are able to modify their transmission powers. The anchors partition the region into non-overlapping areas by changing their power levels. An underwater sensor keeps a list of anchors and corresponding power levels. The sensor node sends this information to the sink. The sink node determines the area in which the sensors resides in. This method gives course-grained location estimates and it is centralized. Hence, it is not suitable for large-scale USNs and for the applications that require accurate, online location estimates.

In [46], the authors aim to solve the localization problem for mobile USNs. The nodes collect distance measurements to their neighbors during the localization epoch. The distance measurements are processed offline to establish localization. This scheme is targeted for applications where the location information is needed once the mission has finished, i.e. the data is tagged at the post processing stage. However, for USNs that need to do online monitoring or for underwater networks with actuators, real-time location information is necessary.

In [47], localization for a hybrid network architecture is proposed. The underwater sensor nodes are stationary and a mobile AUV patrols the network region to localize the sensor nodes. The AUV periodically surfaces to receive GPS coordinates and does dead-reckoning for tracking self location. On its route, from different locations, AUV broadcasts self coordinates. The underwater nodes estimate their location by lateration when they hear more than 3 non-collinear AUV positions. This method has high localization delay, therefore it is not suitable for mobile USNs.

In [48], a prediction-based localization scheme is proposed for mobile underwater sensor networks. The same hierarchical USN as in [5] is used. The anchor node announces the mobility pattern to the ordinary sensors. Ordinary sensors predict their location with this model until they receive an updated model. Here, anchor nodes are able to predict their mobility model and they confirm the accuracy of their prediction via measurements to the surface buoys. If their model is accurate enough they do not broadcast updates. Thus, if the nodes follow a certain mobility pattern, they do not receive unnecessary messages, saving from the communication cost. However, overhead due to the communication between the surface buoys and the anchor nodes is omitted in this work. When the anchors validate their models via long distance measurements the nodes around them will not be able communicate due to interference.

In [4], we propose a multistage localization technique for mobile USNs. In DNRL, the DNR beacons are not propelled therefore it takes some time for them to descend until the vicinity of the nodes that lie at the deeper levels of the network. To speed up the localization process an iterative scheme is added to the DNR technique. The localized underwater nodes are able to become location proxies for their neighbors and the localization is done iteratively. To the best of our knowledge, in [4], the mobile underwater network is simulated via a realistic ocean current mobility model for the first time.

In [49], we introduce Proxy Localization (PL). PL uses the main idea of multi stage localization that the localized nodes are able to announce self coordinates. PL uses the hop count metric to define the “reliability” of a new reference node. The details of PL is given in Chapter 4.

2.6 Data Delivery in Ad Hoc and Sensor Networks

Conventional aquatic networks are composed of floats, drifters or buoys which carry sensors on board. These sensors collect and store data for a certain duration. Later, they transmit their data to a central station via satellite links. This type of communication can be used for environmental monitoring where real time data is not necessary. However, for example when underwater defence is an issue, then the sensor data collected at the aquatic equipments may need to be processed and enforce an urgent action. In such an application scenario, sensor nodes may send their data to sink nodes or they may send data to actuator nodes, i.e. to specific destinations. In underwater sensor networks, applications may require data forwarding or routing. There are previous works on both approaches. In our studies, we prefer a more general term and call this data delivery. The simplest data delivery scheme is flooding. In the flooding algorithm, source node broadcasts a data packet, the neighbors that are in the transmission range of the source receive the packet and broadcast it. Packet is forwarded until it reaches the destination. In the worst case, flooding reaches all the intermediate nodes. This method ensures that the packet reaches the destination unless source and destination are on two disconnected graphs. However, flooding is not efficient in terms of overhead and energy consumption since most of the time it uses more resources than it actually needs. In MANET and sensor networking literature, more sophisticated data forwarding and routing schemes have been developed to deliver data from source to destination effectively. Before discussing data delivery schemes specifically tailored for USNs, we give a brief survey of the large literature on routing in MANETs and data forwarding in sensor networks. Detailed surveys on both fields are available in the literature [50–53].

Routing protocols for USNs may borrow ideas from routing protocols for ad hoc networks. Therefore, we summarize the related work in this field shortly. Moreover, routing approaches in vehicular networks and delay tolerant networks lend ideas to the data delivery schemes in USNs.

Routing protocols for ad hoc networks can be classified as topology-based and position-based protocols. Topology-based protocols depend on the network graph for routing. In mobile networks, keeping the topology up-to-date is an issue. The proposals for disseminating the topology information are grouped under proactive and reactive approaches. Proactive protocols try to maintain the routing tables up-to-date at all times which means the routes are updated even if there is no ongoing communication. This is done by periodic messages, besides every route change or failure triggers a number of messages. In reactive protocols, routes are calculated when needed, which makes them establish routes on-demand.

Both proactive and reactive approaches have their own drawbacks. Proactive protocols pose minimum initial delay whereas reactive protocols need a route discovery phase at least for the first packet. However, it is hard to ensure that the routing tables maintained by proactive protocols are up to date and free of stale entries. If the nodes are mobile, it is likely that a link will be broken frequently. Moreover, knowing a path to all the other nodes the network may not be essential in a USN. Therefore, proactive protocols may not be suitable for USNs. On the other hand, on-demand protocols have some drawbacks, as well. They may become inefficient when traffic load is heavy. Also high mobility may require frequent route discovery where the overhead of the messaging may exceed the actual throughput. Moreover, source nodes flood route discovery messages and due to low signal propagation speed, path setup may take long time.

In mobile ad hoc networks, position-based routing protocols are considered as promising approaches since forwarding decision is done by each node on the fly. Position-based (or geographic) routing protocols eliminate the need for finding a route before sending a packet. If the positions of all the neighbors and the destination is known, a forwarding decision can be made on the way to the destination, for each packet. A detailed survey of position-based protocols are given in [52]. There are hybrid routing techniques, as well. On-demand routing protocols use flooding to send route request packets that determine the path of a data packet before it is injected to the network. Position information can also be used in flooding to make it more efficient. Directional flooding approach (Location-aided routing - LAR) is proposed in [54] to restrict the flooding to a certain area. LAR defines a request zone and expected zone to direct the packets towards the direction of the destination.

Topology-based or position-based routing protocols assume connected networks however networks can be partitioned if the nodes are sparse or some nodes have different mobility patterns than the others. In fact, routing for partitioned networks are studied more in sensor networking literature. Epidemic routing [55] and probabilistic routing [56] are two schemes designed for such partially connected networks. When there is no path from source to destination, epidemic routing randomly exchanges messages, expecting that the messages will be delivered to the destination eventually. Clearly, this protocol is appropriate for mobile networks where the mobile nodes have a chance to encounter with each other at some time. The intermediate nodes become carriers rather than message forwarders. The message exchange of epidemic routing resembles the SPIN protocol for sensor networks. In SPIN [57], a high-level name is assigned to data, called as meta-data. The nodes perform meta-data negotiations before data transmission. In epidemic routing nodes compare their stored messages and receive the missing information from the neighbors. In this way, unnecessary message exchange is avoided. Probabilistic routing combines gossiping with epidemic routing. Gossiping algorithms are designed for sensor networks, as well. These algorithms send data to several randomly selected nodes. This is more efficient than flooding the data and producing too much redundant copies of the same message. Probabilistic routing exchanges summary vectors similar to epidemic routing. It also keeps an encounter history to decide if the node is a good forwarder for the destination. If a pair of nodes do not encounter for a while, the probability for their meeting again is assumed to be low. Epidemic and probabilistic routing perform especially well when the nodes move in groups. If the nodes represent people with PDA's then it is likely that some people will encounter with each other at some gathering place and as they move from one place to the other they act as message carriers. In fact, a similar idea is used in [58] where a sensor network is used to monitor the wild life. Several mobile nodes in a naturel park (e.g. humans, animals, vehicles) are used to carry environmental data such as temperature, humidity, etc. data from disconnected parts of the networks to the other parts. These nodes are called MULEs (Mobile Ubiquitous LAN Extensions). Here, for instance, feeding grounds or water resources are good message exchange environments for animal planted sensors like in ZebraNet [59]. All of those protocols for partially connected networks assume uncontrolled movement of nodes.

In [60], the authors consider message carrying with controlled movement. They assume that either the node movements can be controlled or a mobile node which is called as ferry, is capable of following a defined route. In the first approach, the ferry has a fixed route and the source node moves towards the ferry to upload its messages. The destination does the same to receive the message. In the second approach, nodes are stationary, the ferry approaches to the nodes to receive their data. Then the data is carried to destination. This store-carry-forward approach is found suitable for vehicular networks, as well. In [61], the authors claim that, the motion of the vehicles on highways increase the message delivery ratio. However, store-carry-forward technique is suitable for delay insensitive applications which is a concept also referred in Delay Tolerant Networking (DTN) [62]. In essence, [61] is an implementation of epidemic routing for vehicles. Message carrying idea is pronounced and it recalls message ferrying, but unlike [60], the motion of the nodes (vehicles) is not preplanned. [61] considers sparse vehicular networks with the partially connected network graph. For example, during nighttime on highways, if the vehicles cannot find a next hop, they can store the packet for the possibility of eventually encountering a relay. Obviously, this algorithm is suitable for the vehicles on the highway that follow a straight path. However, in practice the nodes change direction and packets may get lost due to buffer limits.

In [63], velocity information is used for routing in vehicular networks. The authors propose Velocity-Aided Routing (VAR) and Predictive Mobility and Location-Aware Routing (PMLAR). Both of them are geographic routing approaches. VAR chooses the next-hop according to relative speeds between nodes. The best relay is chosen to be the node that is approaching the destination the fastest. It is also mentioned that VAR works best with the mobility patterns like the highway mobility. PMLAR adds destination location prediction to VAR. Since the intermediate nodes are also aware of the velocity and direction of the destination, each forwarding node may refine the location of the destination as the packet approaches the target.

In [64], Direction Forwarding (DFR) is proposed for highly mobile, large-scale ad hoc networks. DFR aims to overcome the stale next hop problem in highly mobile scenarios. DFR combines table-based routing with geo-routing. The routing table includes the ID of the next hop and hop distance to the destination similar to conventional routing protocols. The packet is first forwarded to a next hop based on this routing table. However, due to node mobility the relay node may have moved to a different location. If the node has moved and forwarding fails then the packet is forwarded towards the most promising neighbor in the recorded direction. In the presence of frequent link failures caused by mobility, direction forwarding may increase delivery ratio given that the network is sufficiently dense. In [65], a prediction based routing (PBR) protocol is proposed for estimating the link lifetime. PBR is an on-demand ad hoc routing protocol designed for vehicular networks. PBR initiates a route request before the route is actually broken. The lifetime estimated via the velocity and direction is used to determine the time to initiate a new route. Reactive protocols usually wait for route failure, the early reaction proposed by PBR improves delay and related loss rate. Using link layer information in routing can also be considered for USNs.

Based on previous work and the specific challenges of the underwater environment, data delivery for a USN has to pay particular attention to the following metrics:

- packet delivery ratio
- end-to-end delay
- energy consumption
- scalability
- dynamic topology
- robustness in low bandwidth conditions
- residual lifetime of forwarding nodes
- link quality

In the next section, we summarize the routing solutions proposed for USNs.

2.7 Data Delivery in Underwater Sensor Networks

Although ad hoc routing protocols and sensor network data forwarding techniques may lend some ideas, novel methods tailored for underwater sensor networks should be investigated. In this section, we survey the data delivery approaches in USNs.

In [40] the authors propose a greedy routing approach for USNs. Their aim is to choose the next-hop as the node: i) closest node to the sink, ii) minimizing the energy required to transmit a bit from the node to sink. The latter constraint becomes important for underwater sensor networks because transmission may require multiple trials due to poor channel conditions. Each transmission consumes the battery power of sensor nodes. Considering best available relay upon link quality is not trivial. However, this approach only has a greedy routing phase. When a packet encounters an energy void, i.e. a relay happens to have no other node around satisfying the required energy criteria, it is not clear, how the packet is forwarded.

In [66], another routing technique that is based on location information and minimum energy consumption, is proposed. Focused Beam Routing (FBR), assumes a conic region centered around a straight line between the source and destination where candidate relays may be present. Locations of the source and destination is known but the locations of the intermediate nodes are not necessary known a priori. The source searches for the relays in cone-shaped regions by increasing the transmission range whenever a candidate relay cannot be found at a certain distance, i.e. power level. If increasing the power level in one direction does not help in finding a relay, then the source node shifts its cone and starts searching to the left or right of the main cone.

In [67], the authors propose two routing algorithms for delay insensitive and delay sensitive applications. Generally, data forwarding is closely coupled with application needs. Therefore, it is feasible to have different route optimization criteria for different type of applications. In the delay insensitive applications, the main objective is to minimize the energy consumption, hence to minimize the number of retransmissions by using links with low error rate. The routing algorithm greedily chooses the next hop as the closest node to the sink that minimizes the energy consumption which is similar to [40]. Delay-sensitive routing protocol uses the same idea to make the routing decision since its main objective is to minimize energy consumption as well. In contrast to the delay-insensitive protocol, it does not retransmit the corrupted or lost packets. The protocol defines an upper bound for error and delay, as well.

[30] proposes a resilient, centralized routing protocol to address the route failures due to loss of connectivity, impairments of the acoustic channel in underwater or sensor failure. Routing is defined as an optimization problem where a central node, possibly a surface station, forms primary and backup paths. These paths are chosen such that energy consumption is minimized. A localized network restoration is also considered. This routing protocol is suitable for small-scale USNs with long-term critical missions. In a large-scale network, the cost for centrally updating paths is unaffordable.

In [68], Energy Optimized Path Unaware Layered Routing Protocol (E-PULRP) is proposed. E-PULRP aims to minimize the total energy spent in the underwater sensor network. It is an extended version of PULRP proposed previously in [69]. E-PULRP divides the network into spherical regions which are called as layers. Sink (layer 0) is at the center of the spherical region and it initiates a probe to determine the nodes in layer 1. The nodes that receive the probe above a predefined threshold are accepted as in layer 1. A node in layer 1 sends a probe to determine layer 2 and this goes on iteratively until L layers. Packets propagate from the source node towards inner layers. Each node modifies its transmission energy level according to the layer it belongs to. Routing consists of the following steps. The source node sends a control packet before the data packet. A relay node from the lower layer with the maximum distance to the previous relay and with sufficient energy for packet transmission replies with an ACK. After this phase, data packet is forwarded to the relay node. Relays are chosen on the fly similar to geographic routing, thus, no routing tables are required. A re-layering mechanism is also considered for handling mobility. Energy optimization is done by adjusting a node's transmission energy level which also determines the layer width. To decide on the transmission energy, nodes need to know the total number of deployed nodes besides their distribution in the corresponding area. This assumption may be realistic for stationary underwater sensor networks however for the mobile USN, node distribution may change in time and degrade the performance of E-PULRP.

DUCS [70] proposes a hierarchical routing protocol using clusters. The authors define a cluster formation algorithm where data transmission is scheduled to avoid contention. As for routing, nodes send the packets to the cluster-head and the cluster head routes the packet to the sink with multi hop routing among other cluster heads. Cluster formation and routing are two consecutive steps repeated periodically.

Several position-based algorithms have been considered for USNs. The major challenge of the geographic routing algorithms is to handle void regions. A recent survey [31] on underwater networks highlights the importance of *sparse* and *mobile* networks due to the immense volume of the underwater domain. Therefore, it will be common to have voids in the topology. A detailed survey of void handling techniques can be found in [71]. However, this paper surveys the void handling techniques for terrestrial ad hoc networks where communication is not as challenged as acoustics.

Flooding is the basic and the naive solution to void handling. However, it is too costly even for terrestrial networks especially it is unaffordable for energy-limited sensor networks. Flooding may be restricted to several levels of neighbors but this would not achieve guaranteed delivery. Apart from flooding, all the other proposed schemes are based either on forming a tree or on a location service where a new position can be selected if the packet gets stuck at a void. For underwater sensor networks the solutions surveyed in [71] bring along unaffordable communication overhead. There are few routing protocols that include void avoidance techniques These are summarized after the related routing protocol is introduced in the following paragraphs.

Besides, sparse deployment, mobility makes routing even more challenging in USNs. Maintaining the routes to destinations under mobility, using minimum message exchange is a difficult task. Vector Based Forwarding (VBF) [10] tries to find a solution to this problem in underwater sensor networks. In VBF, each packet contains the positions of the sender, the target (destination) and the forwarder. The packet is routed along a virtual vector from the sender to the destination. When a node receives a packet, it computes its relative position to the forwarder by measuring the distance in between and using the angle of arrival. All the nodes in the communication range of the sender make this calculation and only the nodes close to the *routing vector* forward the packet. The forwarding path is virtually a routing pipe from the source to the target: only the sensor nodes inside this pipe are eligible for forwarding. This multi-path delivery increases the chance of packet delivery. The performance of VBF highly depends on the radius of the pipe. If the network is dense, too many nodes may be involved in forwarding or if it is too sparse then there may be no nodes within the specified pipe radius. This problem is addressed in [72]. Here, a Hop-by-Hop VBF (HH-VBF)is proposed. In VBF the routing pipe between a source and sink is unique, it is calculated at the beginning of data forwarding. HH-VBF allows local decisions, every relay on the way to sink forms its own routing pipe. Another void avoidance technique for VBF is proposed in [73]. If the packet gets stuck in a void, first *vector shift* is applied, if this does not solve the problem *back-pressure* is used. Vector shifts basically works as follows. When a node notices a void region ahead it broadcasts a vector shift request. The nodes that are already in the same vector pipe ignore this request. The nodes outside the pipe try to establish a new pipe from themselves to the target. In this phase, if the node initiating the request cannot find a new pipe, it marks the data packet as back-pressure and broadcasts. Each node receiving this packet, checks if vector-shifting has been done before, if this was already tried then the packet is broadcasted as back-pressure packet again. The main problem of [73] is, when there are too many voids, this may drive the system performance close to flooding.

In [74], Multipath Virtual Sink (MVS) architecture is proposed and compared to VBF. MVS places the sinks around the boundaries of the underwater network and assumes that they are connected via high-speed wireless links. In this case, several beacons form a virtual sink and a copy of a packet is marked as delivered when it reaches one of the sinks. MVS is suitable for a stationary network because it uses reverse path forwarding where the path setup takes place during the initialization period. The packet delivery success of MVS degrades as the link quality decreases. However, it has less end-to-end delay than VBF. This is expected since multiple sinks placed at the network boundaries causes the sources to use the paths that are spatially diverse. This decreases collision and end-to-end delay in return. For a mobile network, it is hard to maintain the sink nodes at the boundaries of the network and also to connect those sinks with high speed links is not practical in real life.

DBR [75] is a position-based routing algorithm for underwater sensor networks. It only uses the depth information to route the packets. The sinks are assumed to be floating above the water and the packet generating sensors are assumed to be floating below the surface. Sensors choose the next relay by looking at the depth information. If the packet comes from a sensor at a deeper level, the packet is forwarded by the neighbor node which is closest to the surface. In this way, the packets bubble up to surface. DBR is a simple greedy scheme where a void in the vertical plane results in packet loss. In [76], the authors propose an adaptive routing approach for a delay tolerant USN. The underwater nodes classify the data packets by priority. The routine monitoring packets and the emergency alarm packets are treated differently. Monitoring packets are allowed to have one copy in the network whereas alarm packets are allowed to have more copies to guarantee delivery. Underwater nodes are assumed to have location information and they use geographic routing in forwarding decisions. Each node chooses the best relay within the “forwarding area” which is a spherical subset of the transmission range. Packet priority determines the size of the forwarding area, i.e. the candidate relays are chosen within a larger area if the priority is higher.

Location-Aware Source Routing (LASR) protocol is proposed for multiple AUVs (Autonomous Underwater Vehicles) in mobile underwater missions in [77]. LASR is a source routing protocol incorporating position and link quality information in route decision. Relative positions of the neighbors are estimated via time of transmission and neighbor ids. These are derived from the acoustic modem and TDMA protocol at the MAC layer. Link quality is estimated via expected number of transmission count metric. LASR tracks the changes in the topology via received transmissions and the link quality metric replaces the hop count metric of DSR. LASR uses cross layer information in routing decision. It is specifically proposed for highly mobile networks. In [77], LASR is reported to outperform DSR in mobile scenarios. However, the protocol overhead of LASR is high since the link quality information is carried in the packets. Moreover, it requires special modem hardware.

In [78], the authors focus on data delivery for the vulnerable underwater acoustic links. They propose producing multiple copies (clones) of a packet at the source node to increase the packet delivery ratio. Multiple copy approach increases the chance of successful delivery however it also increases the overhead and the energy consumption. Moreover, sending more packets than necessary will degrade the overall performance of the network due to collisions. For a single source-sink scenario packet cloning may be useful however when several sources compete for the scarce underwater channel packet cloning is not practical.

There are several works that investigate the possibility of using biologically-inspired, delay-tolerant networks in underwater. In [79], the authors introduce a biological monitoring system using whales as information carriers. The whales are equipped with sensors and communication devises. They collect data, carry it to some other parts of the network and in the meanwhile diffuse it by exchanging with the other whales with some probability likewise gossiping algorithms. When the whales are within the transmission range of an “infostation”, the data is “offloaded”. Infostations are stationary buoys placed on the paths of the whales. Infostations transmit the data to the on-shore processing center for further use.

In [80], a similar approach uses Delay Tolerant Data Dolphins (DDD). The slight difference is that in [80] the mobile collector nodes (dolphins) collect data from the stationary sensors and in [79] mobile nodes (whales) are the sensing nodes themselves. In this aspect, [80] applies data MULEs [58] to underwater.

3. MOBILITY MODEL

In mobile scenarios, sensor nodes are assumed to be drifting with the force of currents. Mobility of the sensors can be modeled by the movement of the currents. However, accurate modeling of ocean currents may be as complex as weather forecast however, in oceanography literature, a computationally efficient kinematic approach has been proposed. Although the assumptions made in this approach do not hold in every case, the model has proven to successfully capture the dynamics of the ocean movement when the floats are calibrated to follow a precisely defined isopycnal surface which is a surface of constant density that can be assumed to be horizontal. This assumption is realistic since the ocean is a stratified, rotating fluid, hence vertical movements are, almost everywhere, negligible with respect to the horizontal ones [81].

The subsurface current model was first introduced in [82] and the model parameters were clearly defined in [83]. In [84], the authors apply this model to USNs. The currents flowing in the subsurface layer are defined by a non-dimensional streamfunction:

$$\psi(x,y,t) = -\tanh\left[\frac{y - B(t)\sin(k(x-ct))}{\sqrt{1+k^2B^2(t)\cos^2(k(x-ct))}}\right] \qquad \textbf{(3.1)}$$

which is a time dependent generalization of the streamfunction defined by Bower in [82], (see [85] and the references therein for details). The streamfunction in (3.1) represents a jet-like current meandering between recirculating vortices. The amplitude of the meanders is modulated by the time-dependent function $B(t) = A + \varepsilon\cos(\omega t)$, and their phase shifts with a speed c. For a wide range of parameters, this function models a chaotic mixing across the current. Following [84], we use $A = 1.2$, $c = 0.12$, $k = 2\pi/7.5$, $\omega = 0.4$, $\varepsilon = 0.3$. By taking one non-dimensional unit of space to be a kilometer, and one non-dimensional unit of time to be 0.03 days, we have that the size of the meanders is 7.5 km, the typical current speed inside the jet is about 0.3 m/s, and

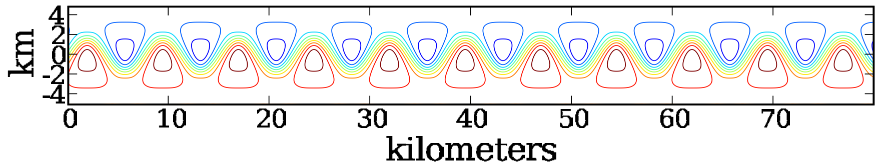

Figure 3.1: Illustration of the meandering current model.

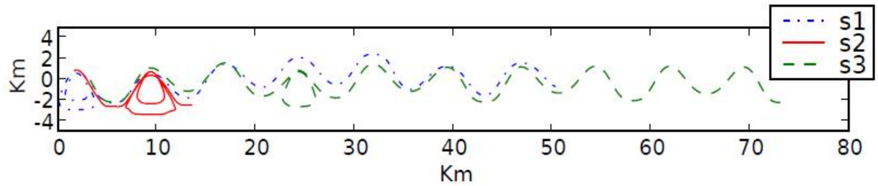

Figure 3.2: Three representative sensor trajectories moving with MCM.

the modulation period is about half a day. With these scalings the streamfunction (3.1) represents a typical coastal current.

This model is named as Meandering Current Mobility model (MCM) [84]. In Figure 3.1, we give an illustration of the MCM model with a point of view from the horizontal plane. In Figure 3.2, we give an illustration of sample trajectories of three sensors. As seen from the figure, some sensors drift with the jet current while some are captured in the eddies for some time and join the main current after a while.

From ψ, the two components (u, v) of a divergenceless, horizontal velocity field are recovered as:

$$u = -\frac{\partial \psi}{\partial y}; \quad v = \frac{\partial \psi}{\partial x}. \qquad \textbf{(3.2)}$$

At the subsurface layer, the current is determined by the large-scale, internal dynamics of the ocean. However, at the surface layer, the motion of the water is directly affected by the local winds. Their interaction and modeling is an active research topic for oceanographers. In [4], we collaborated on adding a simple model for the surface layer to the MCM model. This model assumes that a node floating on the surface has a velocity which is a random perturbation of the subsurface velocity, that is: In order to keep the model simple, the stochastic component (u_s, v_s) is assumed to have no spatial dependence. Also, the stochastic process used to generate (u_s, v_s) needs to have

$$(u,v)_{\text{node}} = (u,v)_{\psi} + (u_s, v_s). \tag{3.3}$$

a finite self-correlation in time, and a finite variance. The simplest model that fits these requirements is the Ornstein-Uhlenbeck process described by the Langevin equation:

$$udt + \sqrt{2\lambda U^2}dw \tag{3.4}$$

where $w(t)$ is a Wiener process, the positive constants λ and U are the inverse of the decorrelation time and the root-mean-squared speed of the wind [86, 87], respectively. The v component of the velocity is described by the same Langevin equation, with an independent Wiener process.

In practice, the velocities are computed at discrete time intervals, so we use the following discrete expression of (3.4)

$$u_s(t+\Delta t) = u_s(t)e^{-\lambda\Delta t} + U\sqrt{1-e^{-2\lambda\Delta t}}\zeta_i \tag{3.5}$$

$$v_s(t+\Delta t) = v_s(t)e^{-\lambda\Delta t} + U\sqrt{1-e^{-2\lambda\Delta t}}\xi_i \tag{3.6}$$

where ζ_i and ξ_i are independent pseudo-random numbers from a zero-mean, unit-variance Gaussian distribution. The parameters are chosen as: $\lambda^{-1} = 2$ days, $U = 0.5$m/s. In our simulations, we use the MCM-SE (MCM with surface effects) model to compare the performance of DNRL, PL and LSL techniques.

4. LOCALIZATION FOR UNDERWATER ACOUSTIC SENSOR NETWORKS

In this chapter, we introduce our proposed localization techniques, Dive and Rise Localization and Proxy Localization. We also give the details of Large Scale Localization which is used for comparison.

4.1 Dive and Rise Localization (DNRL)

In the long-term oceanographic missions, the common approach for localization has been the Long Base-Line (LBL) technique which is based on placing long range pingers on the ocean surface. In these missions, nodes are usually placed kilometers apart and collect data individually. The nodes transfer the collected data to a center station via satellite links. They do not communicate with each other. Thus, they do not form a network. However, the current oceanographic applications demand networking. As the need for networking emerges, in order to achieve higher data rates, range between the sensors has to be decreased. For localization in such an underwater sensor network, the long range pingers should be replaced with short range alternatives. In this case, the location information needs to be forwarded iteratively to the nodes that are not in the transmission range of the surface buoys or some mobile nodes need to deliver the GPS driven coordinates by moving to the vicinity of the underwater nodes. To extend the global location information of the GPS service to the underwater environment, we proposed the DNRL technique in [3].

DNRL uses mobile beacons to distribute the GPS driven coordinates to the underwater sensor nodes. DNR beacons learn their coordinates while they are floating on the surface of the ocean. Then, they periodically descend to the deepest level of the network and ascend to the surface to receive their current location. While descending and ascending, DNR beacons broadcast localization messages at intervals denoted

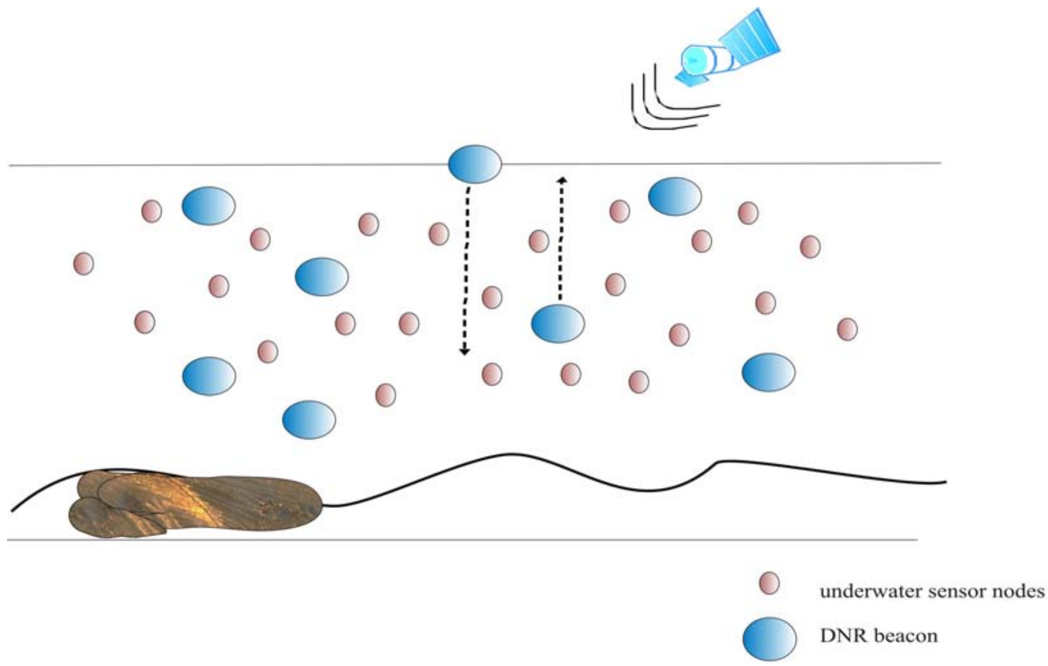

Figure 4.1: Illustration of DNR architecture.

as T_b. It is assumed that DNR beacons can track their locations using a simple compass and an accelerometer during the time spent under the water. They update their coordinates and learn true location when they reach to surface. The underwater nodes estimate their location by passively listening to these messages, hence we may assume that they spend little amount of energy for the localization process. The DNRL architecture is illustrated in Figure 4.1.

A localization message includes a timestamp field and the three dimensional coordinates of the DNR beacon. The timestamp field is used to calculate the distance between the beacon and the node, by using the ToA technique. Since the acoustic signal travels slower than the radio signal it is appropriate to multiply the difference between the arrival time and the timestamp with the speed of sound to get the distance between two nodes. We assume the nodes are synchronized and the speed of sound is constant around the network region. In DNRL, when the underwater node hears from three or more beacons it calculates self coordinates via lateration.

Lateration can be used to estimate n coordinates if there are $n+1$ or more beacon messages. The method is based on the idea of intersecting circles. It is a widely recognized technique which is also used in the GPS system. Lateration works as follows; the coordinates of a node is estimated by using a set of equations:

$$(x-x_i)^2+(y-y_i)^2+(z-z_i)^2=d_i^2 \tag{4.1}$$

where i denotes the beacon ID, (x_i,y_i,z_i) are the coordinates of the beacon and d_i is the measured distance between the beacon and the node. Note that three independent equations are sufficient for solving this nonlinear equation system for (x,y). Since the sensor nodes have pressure sensors on board, the depth information, i.e. the z coordinate is already known. By subtracting the $(n+1)^{th}$ equation from the first n equations, the system is linearized. Then, we solve $A\varphi=b$ where,

$$A=\begin{bmatrix} 2(x_1-x_n) & 2(y_1-y_n) \\ . & . \\ . & . \\ . & . \\ 2(x_{n-1}-x_n) & 2(y_{n-1}-x_n) \end{bmatrix} \tag{4.2}$$

$$b=\begin{bmatrix} x_1^2-x_n^2+y_1^2-y_n^2+z_1^2-z_n^2-2z(z_1-z_n)+d_n^2-d_1^2. \\ . \\ . \\ x_{n-1}^2-x_n^2+y_{n-1}^2-y_n^2+z_{n-1}^2-z_n^2-2z(z_{n-1}-z_n)+d_n^2-d_{n-1}^2 \end{bmatrix} \tag{4.3}$$

The coordinates $\hat{\varphi}=[\hat{x}\ \hat{y}]^T$ are estimated by using a least-squares approach: $\hat{\varphi}=(A^TA)^{-1}A^Tb$.

In DNRL, a node is considered as a localized node if the estimation error is less than the communication range, R. The error, ε, is defined as the average difference between the estimated distances and the measured distances [88]. Estimated distances are the distances between the estimated coordinates of the node and the beacon coordinates. Measured distance is the distance calculated via ToA.

If $\varepsilon>R$ then the node is marked as non-localized. Since the localization is done periodically a non-localized node may become localized later and the localized nodes may refine their estimates.

Each sensor node is assumed to have a limited memory space allocated for storing localization messages. These messages are kept in a localization table. A table entry has *beacon id, coordinate, distance and timestamp* fields. When a node receives a localization message from a beacon it first checks if there is a previous entry from this

$$\varepsilon = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_i-\hat{x})^2+(y_i-\hat{y})^2+(z_i-z)^2}-d_i \qquad \textbf{(4.4)}$$

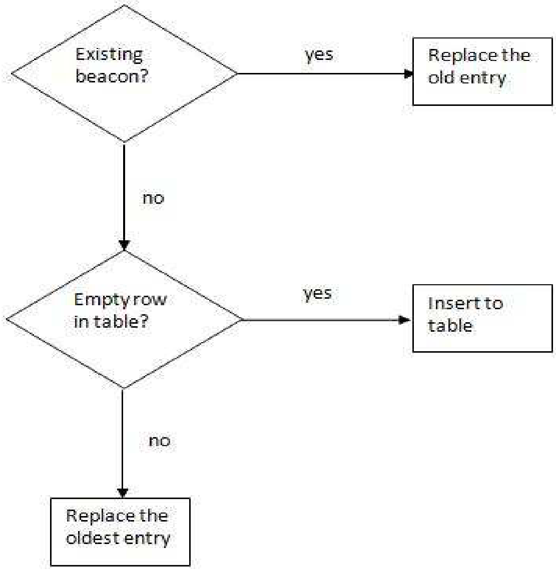

Figure 4.2: Flowchart of the table update algorithm in DNRL.

beacon. If there is a previous entry, the new message replaces the old entry. If the localization message comes from a beacon that is heard for the first time, then, the sensor node checks if it has space in the table. The message is placed in the table if there is empty space. If the table is full, then it replaces the oldest message. The flowchart of the algorithm is given in Figure 4.2.

Since we consider a mobile network, DNRL, PL and LSL periodically refresh their localization tables. Each localized node flushes its table after a period of T_r.

4.2 Proxy Localization (PL)

Proxy Localization (PL) [4], extends DNRL to include the localized underwater nodes in the set of beacons. PL uses the DNRL technique to localize the upper portion of the network. The DNR beacons descend until the mid-depth of the three dimensional USN. The localized nodes become the location proxies for the nodes floating at deeper levels. Location proxies announce self coordinates. The PL architecture is illustrated in Figure 4.3. The unlocalized underwater nodes may use the coordinates of the proxies in lateration and localize themselves. An unlocalized underwater node uses the hop count metric to choose the “reliable” proxies among the candidates. Hop count is the hop distance between a proxy node and a beacon. At the iterative phase, error

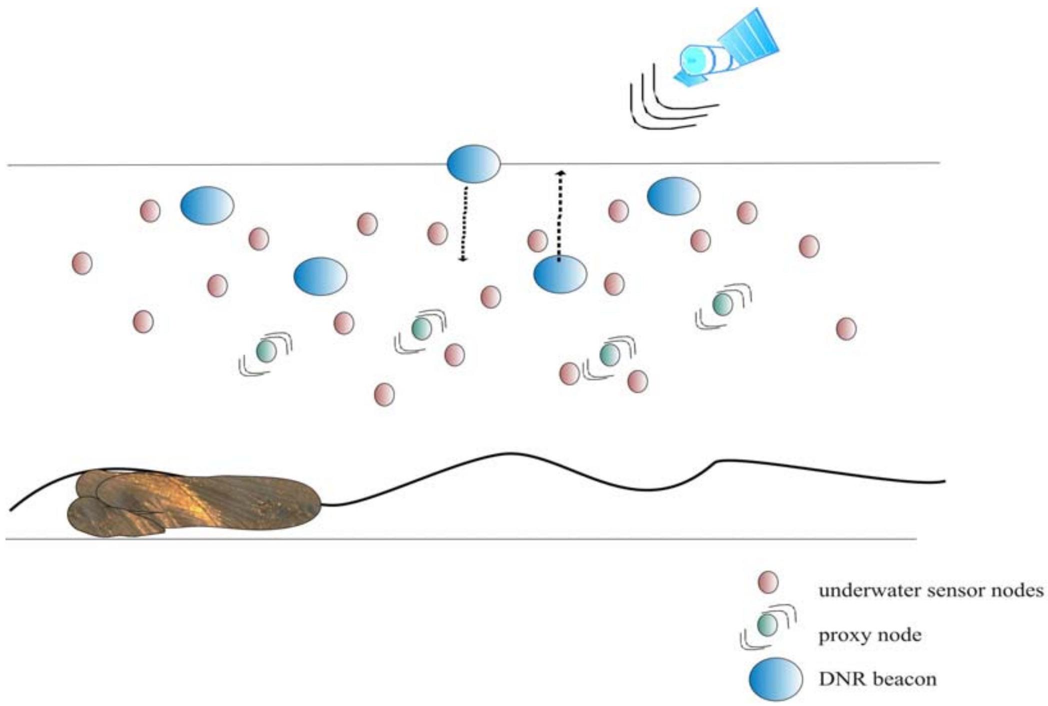

Figure 4.3: Illustration of PL architecture.

accumulates at the proxy nodes that are distant from the beacons. Therefore, proxy nodes with the least hop distance to the beacons are preferred in lateration equations.

The packet format of PL is given in Fig. 4.4. Coordinates are used in lateration. Distance is measured by ToA of the messages by using the timestamp field. The Maximum Dive Depth (MDD) field limits the number of proxy beacons. Localized sensors may become proxy nodes only if they lie below the maximum dive depth of the DNR beacons. This controls the protocol overhead. The Hop Count (HC) is the cumulative hop distance between the beacons and the node as explained above.

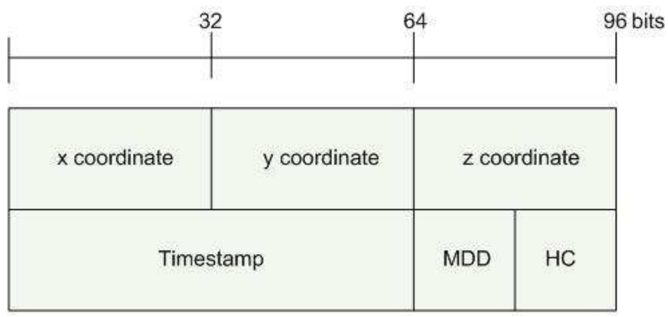

Figure 4.4: Localization packet format for proxy localization.

In PL, a proxy node may help localizing its neighbors and later, a localized neighbor may send an update to the proxy node. To prevent the ping-pong effect on message

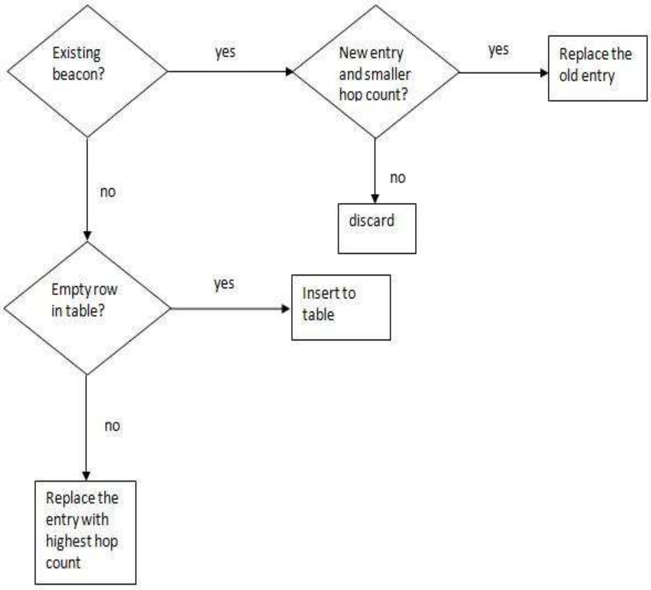

Figure 4.5: Flowchart of the table update algorithm in PL.

propagation, messages with higher timestamp and lower hop count are used in lateration.

In PL, each node keeps a limited number of messages in the “localization table”, similar to DNRL. Localization table keeps the anchor ID, anchor coordinate, timestamp and hop count. When a node receives a localization message from a beacon or a proxy, it first checks if there is a previous entry from this node. If the timestamp is fresher, then the hop count is checked, if it is smaller the new message replaces the old entry, else it is discarded. If the message comes from a newly heard beacon or proxy, then, the sensor node checks if it has space in the table. The message is placed in the table if there is empty space. If the table is full, then it replaces the entry with the highest hop count. The flowchart of the algorithm is given in Figure 4.5.

4.3 Large Scale Localization (LSL)

Large Scale Localization (LSL) is proposed for large-scale, distributed localization in underwater sensor networks [5]. LSL is a hierarchical localization scheme. There are three types of nodes: “surface buoys”, “anchor nodes” and “ordinary sensor nodes”, as shown in Figure 4.6. Surface buoys are anchored on the surface level. Surface buoys learn their coordinates through GPS. “Anchor nodes” and “ordinary sensor nodes” float at several depths in underwater. Anchor nodes are spread among the whole sensor network and they are localized by the surface buoys. In [5], the authors consider

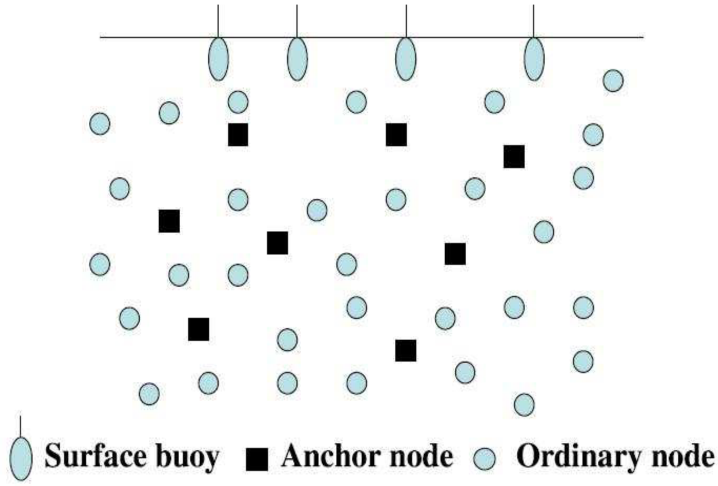

Figure 4.6: Illustration of LSL architecture from Cui et al., 2007.

only the localization of ordinary sensor nodes. The ordinary sensor localization is as follows. The anchor node broadcasts a localization message that includes its coordinates. In addition to these localization messages, all the nodes make periodic beacon exchanges to measure the distances to their neighbors. If an ordinary node gathers enough localization messages (e.g three for localization in 3D where the depth information is retrieved from the pressure sensor) it performs lateration to estimate self coordinates. A localized ordinary node can become a reference (or proxy) if its confidence value is above a threshold. The localized node calculates its confidence value, η, as shown in 4.5:

$$\eta = \begin{cases} 1 & \text{, if the node is an anchor} \\ 1 - \frac{\sum_i \left|(\hat{x}-x_i)^2+(\hat{y}-y_i)^2+(z-z_i)^2-d_i^2\right|}{\sum_i (\hat{x}-x_i)^2+(\hat{y}-y_i)^2+(z-z_i)^2} & \text{, otherwise} \end{cases} \quad \textbf{(4.5)}$$

where $(\hat{x},\hat{y})$ are the estimates for (x,y) coordinates, (x_i,y_i,z_i) are the coordinates of the anchor nodes and d_i is the measured distance between the node and the anchor.

If the number of localization messages are not enough to estimate the self location, the node broadcasts the received localization messages along with the distance measurements to its neighbors and anchors/reference nodes. A non-localized node uses these anchor coordinates and distance measurements in Euclidean distance estimation algorithm. Euclidean distance estimation is used in order to add the anchors that are two hops away. In [5], the two dimensional Euclidean algorithm of [89] is extended for the three dimensional case. The key idea of three dimensional Euclidean distance

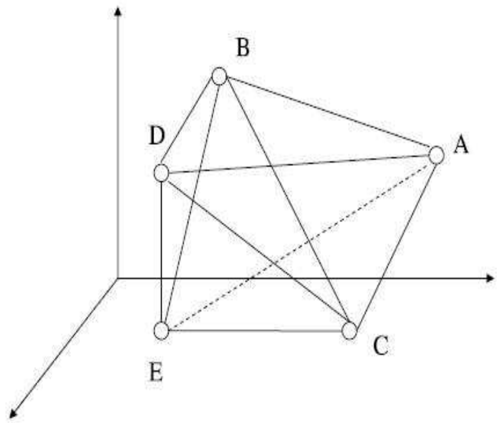

Figure 4.7: Three dimensional euclidean estimation from Cui et al, 2007.

estimation is to estimate the distance between two nodes that are two-hops away by using one-hop distance measurements. Figure 4.7 shows an example topology. For example, say node E has heard the coordinates of node A from its neighbors but it needs the distance in between to use in lateration. Therefore, node E wants to estimate its distance to anchor node A. Node E needs to have at least three neighbors (B, C and D) which have distance estimates to A. Moreover, E should have the length information of EB, BA, EC, CA, ED, DA, DB, DC, and BC edges. In the Euclidean distance estimation method, nodes A, B, C and D should not be coplanar and any three nodes out of A, B, C, D and E should not be collinear. Here, node E uses the edges BA, CA, BC to construct the basic localization plane. Since the lengths of edges DB, DA and DC are already known, the relative position of D is estimated by lateration. E also estimates its relative location by lateration using B, C and D. After that, based on the relative locations of node E and A, node E calculates the Euclidean distance to node A.

The Euclidean distance estimation method requires the nodes to keep the distance estimates to their neighbors and anchors in a table and these tables have to be exchanged periodically among neighbors so that the non-localized nodes may collect the necessary information to run the Euclidean distance estimation algorithm.

In LSL, the confidence values of beacon nodes are set to 1. During the localization process, each beacon node broadcasts a localization message periodically. Non-localized nodes are allowed to forward these messages but there is a threshold, *N*, to limit overhead. A non-localized node broadcasts its localization table and neighbor

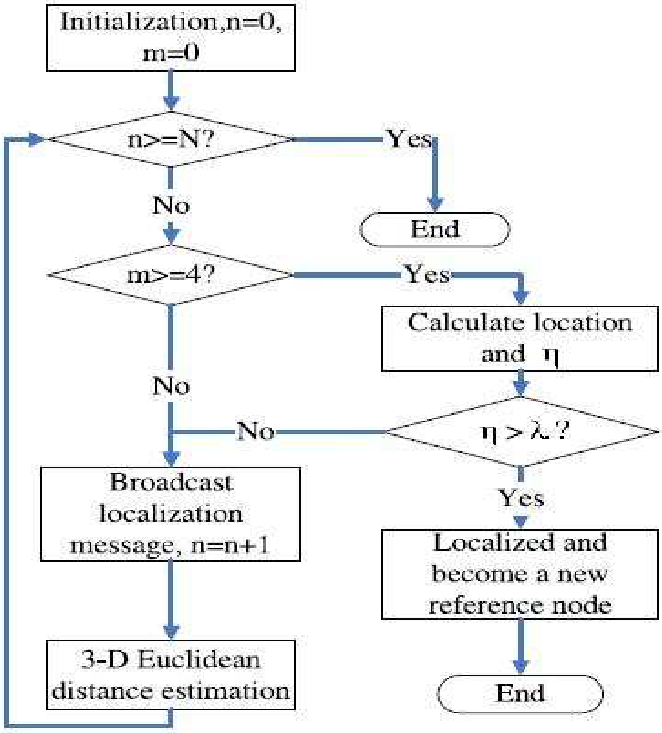

Figure 4.8: Ordinary node localization procedure in LSL from Cui et al, 2007.

table. The neighbor table includes the distance estimates to neighbors and localization table includes the coordinates of the beacons. A non-localized node may estimate self coordinates when it hears from 4 or more anchors. Upon localization, it calculates the confidence value. If the confidence value is above the threshold it broadcasts self coordinates. The flowchart of the algorithm is given in Figure 4.8. m is the number of beacons heard, n is the number of messages forwarded, N is the threshold to forward localization messages, λ is the confidence threshold and η is the confidence value.

5. SIMULATION RESULTS: LOCALIZATION IN MOBILE UNDERWATER SENSOR NETWORKS

We use the QualNet simulator [90] to compare the performance of the localization schemes. The acoustic physical layer is implemented with 50 Kbps of data rate and a channel frequency of 100 KHz. We assume a two ray path loss model. The speed of sound is chosen to be 1513 m/s. We place the nodes in a (1000, 1000, 600) volume. We compare the performance of the localization protocols under i) high-connected network, and ii) low-connected network. In the highly-connected network the transmission range is set to 180 m and for 250 nodes the average node degree is 9. In the sparsely-connected network the transmission range is 150 m where the average node degree is 5.7 for the same number of nodes. For each topology (generated with a different seed), we run simulations to count the average number of neighbors of each node to determine the average node degree.

We vary the beacon percentage for each simulation. Among 250 nodes, we have 10, 15, 20, 25, 30 and 35 percent beacons. Here, we define the beacon percentage as the percentage of the beacons at the initial deployment phase. For the PL and the LSL method, beacon percentage increases as the underwater nodes become proxies and contribute to localization.

Our main objective is to compare our proposed localization protocols, DNRL and PL, with another protocol from the literature, LSL, for a mobile underwater sensor network. In the mobile USN, the nodes are allowed to drift in a 20km x 20km domain. Their motion follows the MCM-SE model. We also give simulation results for a stationary (tethered) network in Appendix A. In the stationary network, the underwater nodes do not move, they are assumed to be floating at a fixed position. The simulations last 6000 seconds.

In the DNRL and PL techniques, mobile beacons ascend and descend using a mechanical technique, i.e. volume expansion, therefore they have a low vertical velocity of $v_d = 1$m/s. They broadcast localization messages with T_b = 100 s intervals. Proxy nodes have the same period T_s = 100 s. Each underwater node keeps $M = 4$ entries in the localization table. In LSL, the localization messages which include the coordinates of the anchor nodes are sent at 100 s intervals. The beacon exchange messages that are used in distance estimation are also sent at 100s intervals and the neighbor tables are exchanged at 200 s intervals. Localization and neighbor tables are used in the Euclidean algorithm to discover the Euclidean distance to the anchors that are two hops away. The neighbor tables contain the largest amount information exchanged between the nodes therefore its frequency is kept less to avoid high overhead. In the LSL technique, a localized node can become a reference node if its confidence is above a pre-defined threshold. Here, we set this threshold to 0.98 following the original paper [5]. For all methods the refreshment period, T_r, is selected as 500 s. The simulation parameters are summarized in Table 5.1

Table 5.1: Simulation parameters for localization in mobile underwater sensor networks

Property	**Value**
Data rate	50Kbps
Loss model	Two-ray
Speed of sound	1513m/s
Medium Access Protocol	CSMA
Volume	1000 x 1000 x 600
Total number of nodes	250
Transmission range	150,180 m
Node degree	5.7, 9
Initial beacon percentage	10, 15, 20, 25, 30, 35
DNR beacon vertical velocity	1m/s
Mobility model	Meandering Current Mobility Model
Localization message interval	100s
LSL beacon exchange	100s
LSL anchor table exchange	100s
LSL neighbor table exchange	200s
LSL confidence interval	0.98
Simulation duration	6000s
Number of simulation runs	50
Confidence interval	0.90

We give the average values of 50 simulation runs. We present the 90% confidence intervals in the figures. The performance of the three localization techniques is

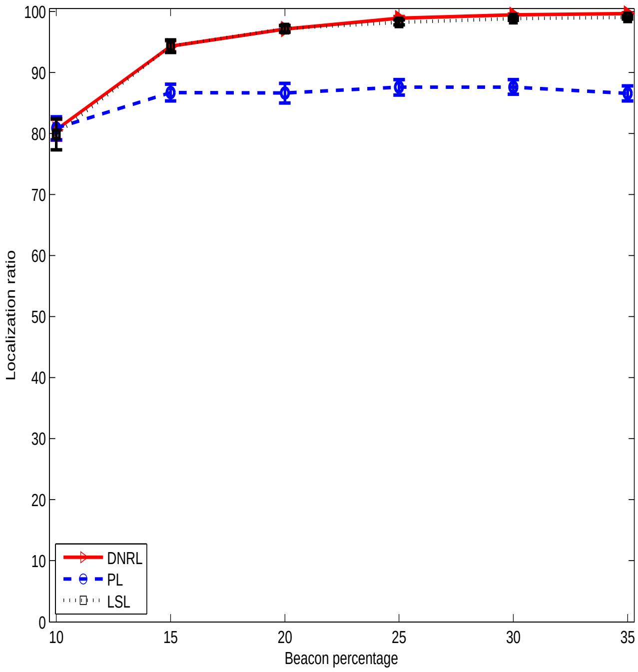

Figure 5.1: Localization ratio for the DNRL, PL and LSL schemes for a highly-connected mobile underwater sensor network.

analyzed in terms of localization success, communication cost, accuracy and energy consumption. We also provide the evolution of localization success with respect to time.

In the following sections, we first present the highly-connected mobile network simulation results and then the sparsely-connected mobile network results.

5.1 Localization Success

Localization success is the ratio of the localized nodes to the total number of nodes. The localization success of DNRL, PL and LSL, for a highly-connected mobile underwater sensor network is given in Figure 5.1. PL has less localization success when compared to DNRL and LSL. In this Figure, DNRL and LSL seems to have identical performance. However, when we zoom in as in Figure 5.2, we observe that for beacon percentages over 20% DNRL as slightly better performance. Using a large number of beacons, DNRL and LSL are able to localize almost all of the underwater nodes and PL can localize 85% of the nodes. Using a beacon percentage of 10%, all three methods are able to localize 80% of the nodes.

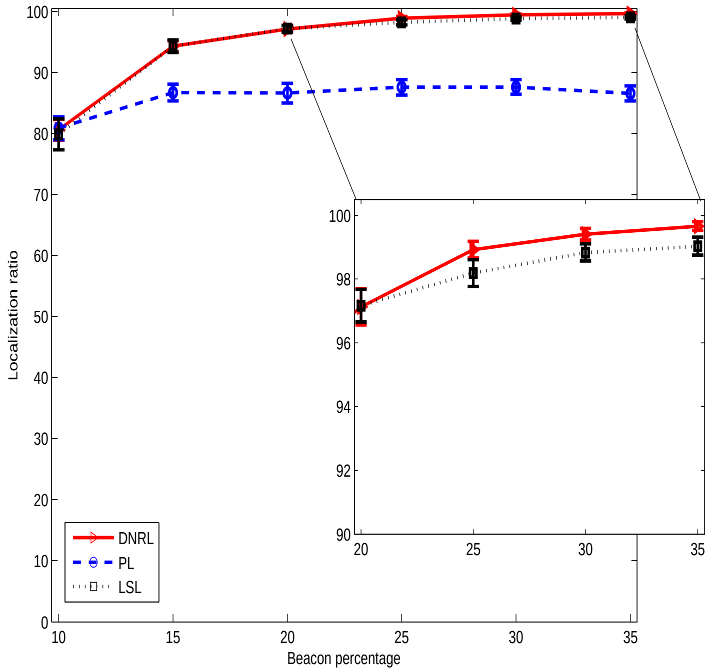

Figure 5.2: Zoomed in version of Figure 5.1

In Figure 5.3, we give the localization success under a sparsely-connected mobile USN. Here, the performance of LSL drops dramatically when the beacon percentage is lower than 35%. In LSL, localization is done by the information gathered from the anchor nodes and the neighbors. Therefore, connectivity plays a key role in the performance. In Figure 5.3, when the beacon percentage is 10% only 20% of the nodes are localized by LSL and only at beacon percentage of 20%, LSL manages to localize a little more than half of the nodes. PL almost has the same localization success as in high connected scenario, likewise DNRL. Localization success is important since the localized underwater sensor nodes become capable of tagging the collected data. However, it is not the only metric to show that a technique is superior to another. Accuracy, communication overhead, energy consumption and the time it takes to localize the nodes are other significant evaluation metrics.

In order to show the bias of estimation with lateration method, we plot the true locations and estimated locations of the nodes. In Figures 5.4, 5.5 and 5.6 we take a snapshot of the network and show the locations of nodes at depths of 200m, 300m and 500m, respectively. We use the topology with 20% beacons and the average nodal degree is 9. The true locations are shown by circle signs and estimated locations are

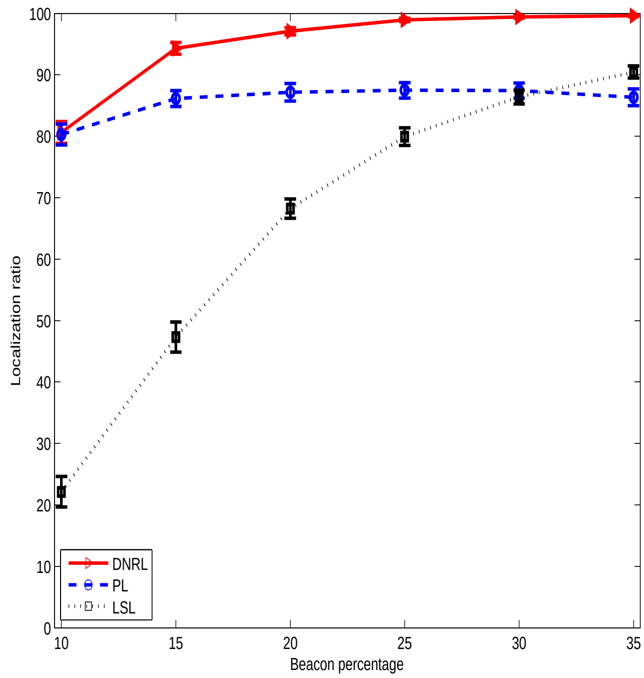

Figure 5.3: Localization ratio for the DNRL, PL and LSL schemes for a sparsely-connected mobile underwater sensor network.

denoted by plus sign. The blue lines illustrate the distance between true and estimated locations. In Figure 5.4, the estimation errors of x and y coordinates do not have a certain pattern or trend. The estimated locations are close to true locations. As the depth increase estimation errors increase as seen from Figure 5.5. In Figure 5.6, at 500m, the estimation errors increase and the estimated positions tend to have higher x and y values than original coordinates.

5.2 Communication Overhead

Communication overhead is the average number of localization messages sent by a single node. In DNRL, only the DNR beacons send messages, the underwater nodes are passive listeners. In PL and LSL underwater nodes may also act like beacons after they learn their location. In LSL, a localized underwater node announces its location if its location estimation error is under a threshold. This is controlled by the confidence value. However, non-localized sensor nodes also send messages to announce the coordinates of their neighboring ordinary sensor nodes and anchor nodes.

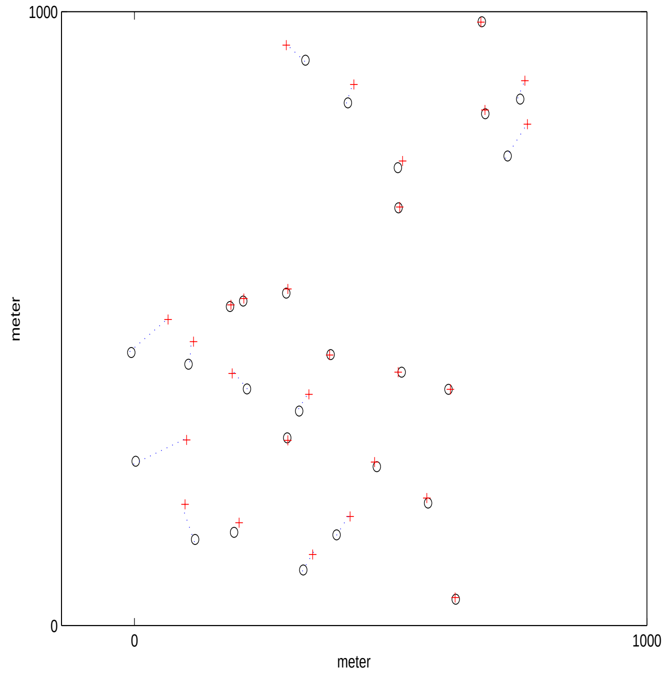

Figure 5.4: True and estimated locations of sensor nodes floating at a depth of 200m.

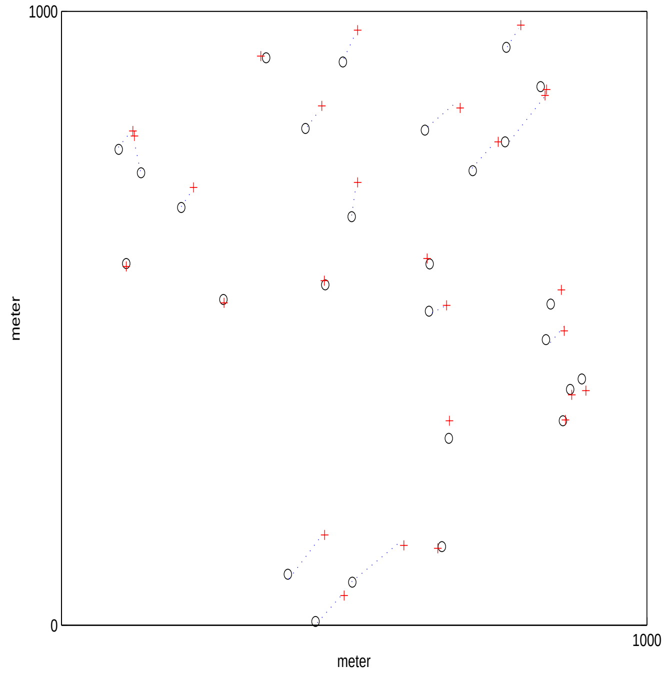

Figure 5.5: True and estimated locations of sensor nodes floating at a depth of 300m.

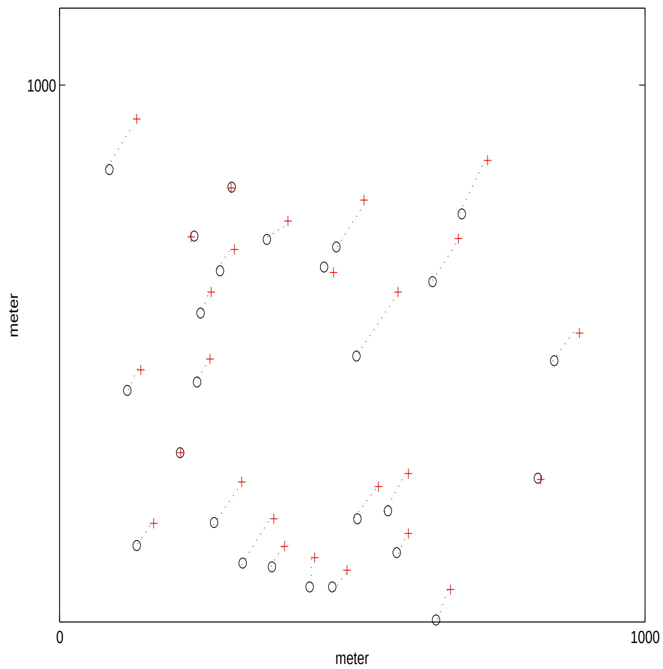

Figure 5.6: True and estimated locations of sensor nodes floating at a depth of 500m.

In Figure 5.7, we give the communication cost for the highly-connected mobile USN. The communication cost of PL is higher than the DNRL and the communication cost of LSL is significantly higher than both of the techniques. The additional messages sent in LSL increase the overhead. In underwater environment, the bandwidth is scarce and localization is not the only required protocol to run in a USN. There may be data forwarding or maintenance tasks, as well. Clearly, the high communication overhead is a handicap for LSL. Moreover, as the number of sent and received packets increases, the lifetime of the underwater network decreases, unless a sustainable method of recharging batteries is found.

In Figure 5.8, we give the communication cost for the sparsely-connected mobile USN. Once more, the overhead for LSL is 5-10 times more than PL and DNRL. However, we observe that as the beacon percentages increase, the overhead of LSL decreases. Actually, as the number of beacons increases, the number of localized nodes increases and this directly affects the overhead. In LSL, non-localized nodes broadcast location and neighbor tables, whereas localized nodes only broadcast their coordinates. Thus a low localization ratio ranslates to high overhead. This is also observed in Figure 5.7,

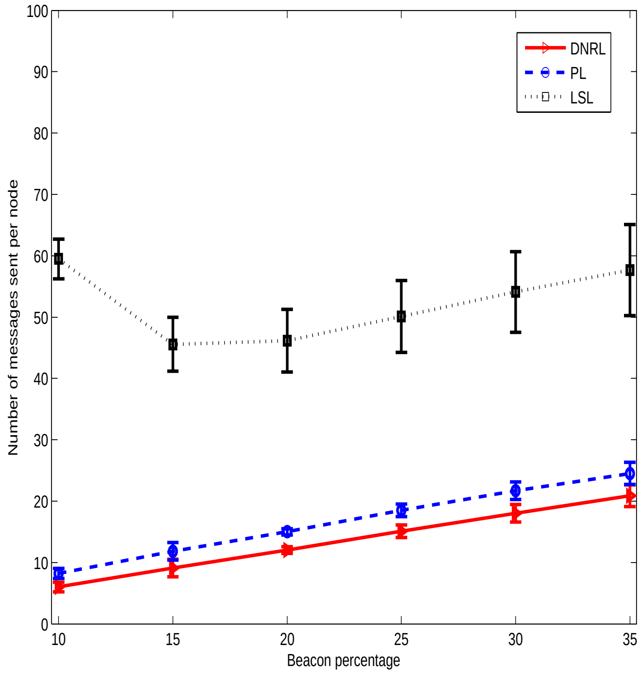

Figure 5.7: Total number of sent messages per node for the DNRL, PL and LSL schemes for the highly-connected mobile underwater sensor network.

where the number of messages per node decreases from 60 to 45 as the localization ratio increases from 80% to 95%.

5.3 Localization Accuracy

Localization accuracy is defined as the mean error ratio. Mean error is the average of the differences between the estimated and the true locations of the nodes. It is divided to communication range to get the mean error ratio scaled to the range. In Figure 5.9, we present the mean error ratio for the mobile USN. The accuracy of the protocols usually increases as the number of beacons increases. PL has the highest error ratio which is above 80 meters for all beacon percentages. Such mean error values are large when compared to an ordinary sensor network however, the large and 3D ocean environment may be tolerant to such accuracy levels. In PL, the reliability of a proxy node is determined by hop count which is the total hop distance from the beacons. The hop count of a beacon is zero and it is preferred over a proxy when two localization messages arrive from a proxy and a beacon. The confidence intervals of PL is also larger than the other methods because the location estimates have high variance. In PL, DNR nodes dive until a certain depth. The nodes that float above this depth prefer DNR

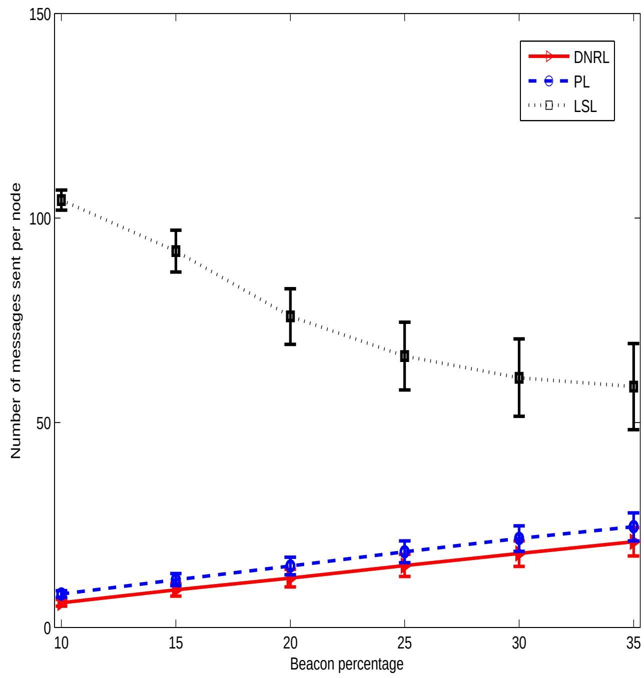

Figure 5.8: Total number of sent messages per node for the DNRL, PL and LSL schemes for the highly-connected mobile underwater sensor network.

locations in the lateration equations due to lower hop count. At deeper levels, nodes can only hear from proxy beacons and hence, have less accurate location estimation. In this heterogenous environment, the variance of the accuracy increases. In the other techniques, anchor nodes are distributed homogeneously, therefore their confidence intervals are tighter. In Figure 5.9, the mean error ratio of LSL decreases to acceptable values for beacon percentages above 25%. The mean error of DNRL is lower than 40 meters for all beacon percentages. DNRL has the highest accuracy among the three methods.

In Figure 5.10, for a sparsely-connected network, the accuracy of DNRL is approximately the same as for the highly-connected scenario. PL performs worse for a low connected network and low number of beacons. When the network is low connected and mobile, with low beacon percentages a large number of nodes use proxy coordinates which become stale in time due to mobility. Note that DNR beacons and the anchors of LSL have absolute location information due to their dead-reckoning ability. Dead reckoning ability introduces a cost therefore we assume only several nodes are equipped with dead-reckoning hardware. LSL with 10% beacon percentage

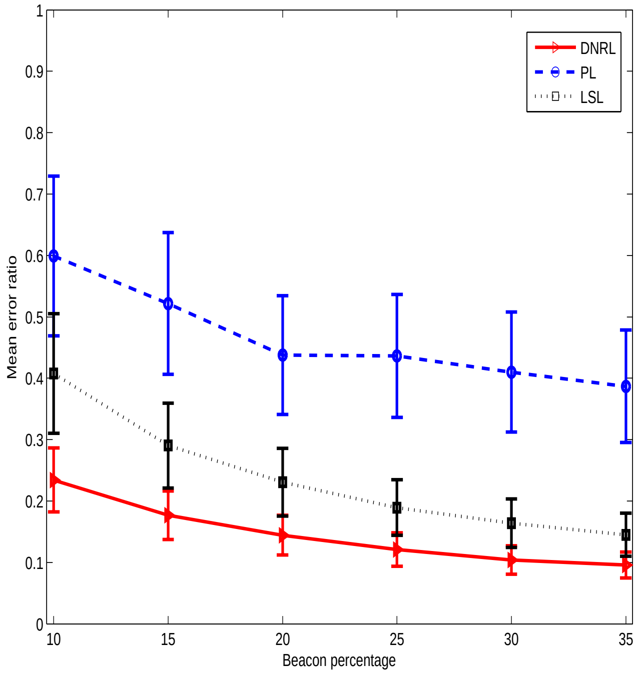

Figure 5.9: Mean error ratio for the DNRL, PL and LSL schemes for a highly-connected mobile underwater sensor network.

seems to have lower error however, this is misleading because in this setting the number of localized nodes are very few.

In order to analyze the impact of the sanity check mechanism on the accuracy, we run DNRL protocol without the sanity check. The sanity check is a part of lateration and DNRL, PL and LSL makes this check. Therefore, we use only one of the protocols, i.e., DNRL. In Figure 5.11 and Figure 5.11, we show the results for highly-connected and sparsely-connected network. For both scenarios, the mean error ratio slightly increases when sanity check is not used.

5.4 Energy Consumption

In Figure 5.13, we give the energy consumption of the localization protocols. Energy consumption depends on several parameters however, a significant amount of energy is spent while transmitting data. Since we assume an acoustic network, the underwater nodes use acoustic modems. Most of the off-the-shelf acoustic modems have high ranges because they are designed to work in applications where the distance between the nodes are on the orders of kilometers. However, for a sensor network to be

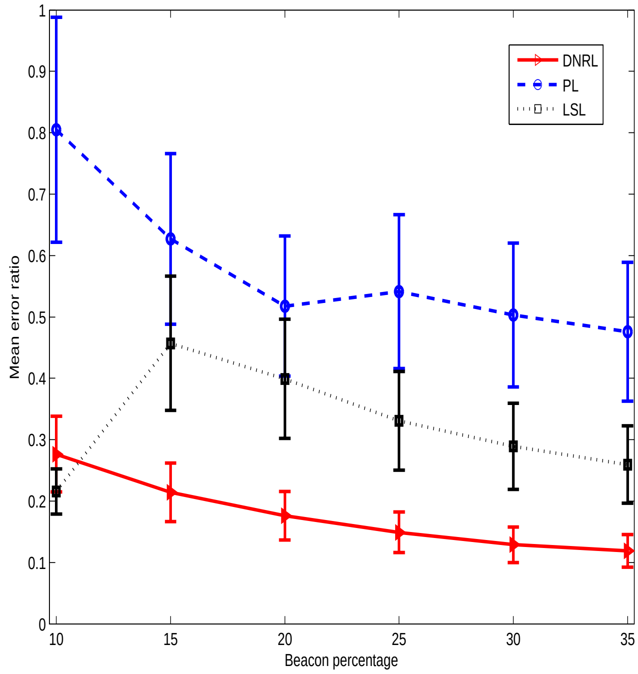

Figure 5.10: Mean error ratio for the DNRL, PL and LSL schemes for a sparsely-connected mobile underwater sensor network.

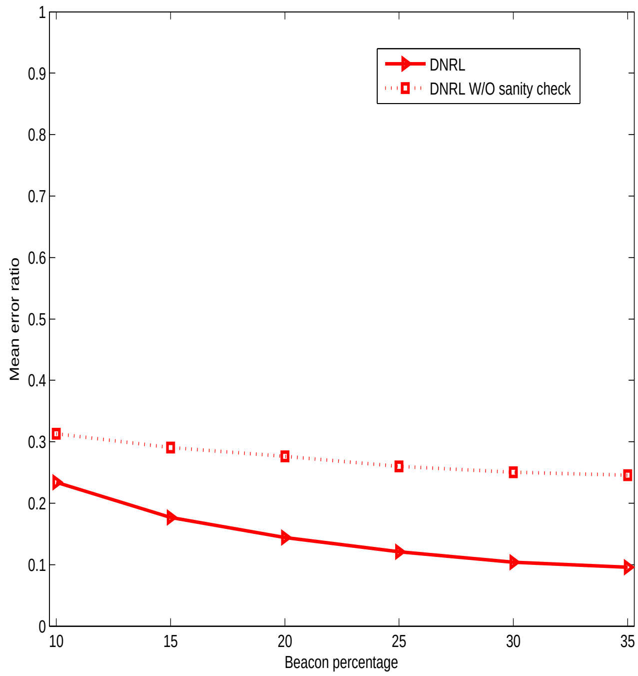

Figure 5.11: Mean error ratio for the DNRL, and "DNR without sanity check", for a highly-connected mobile underwater sensor network.

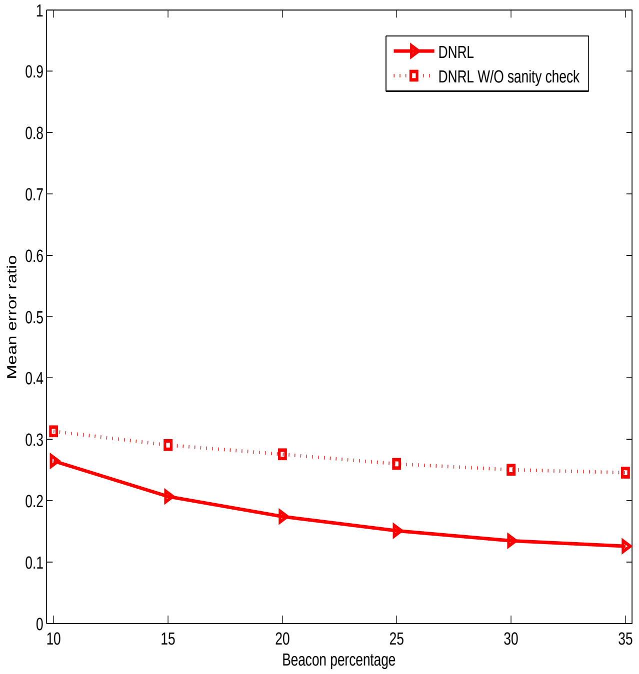

Figure 5.12: Mean error ratio for the DNRL, and "DNR without sanity check", for a sparsely-connected mobile underwater sensor network.

functional the distance between the nodes should be in the order of several hundred meters. As the distance increases, the data rate drops due to the range-bandwidth product limitation. A low range acoustic modem is the Aquacomm modem [35]. Its range is 200 meters and it can transmit 480 bps. In [38], the energy required to transmit one bit is given as 4.5mJ per bit. In Figure 5.13, we use the average number of transmitted bits to calculate the energy consumption. It shows that the energy consumption of LSL is much higher than PL and DNRL. It is even worse for sparsely-connected scenario, as presented in Figure 5.14. An example system that uses Aquacomm modems is the Aquafleck underwater sensor nodes [38]. These nodes are powered by three alkaline cells that have approximately 27Wh or 100kJ. Roughly the localization protocols run for 100 minutes and PL and DNRL spend 20J where LSL spends at least 100J. In this case, even if no other tasks were performed and no energy were spent for receiving, with repeated localization, PL and DNRL would drain the battery approximately in one year yet LSL in only six months for the best possible scenario (35% beacon percentage in highly-connected mobile USN.) Moreover, in Figure 5.14, in a low connected network LSL sends more information (more bits leads to more energy) to carry out the localization by the help of the neighbor nodes. In

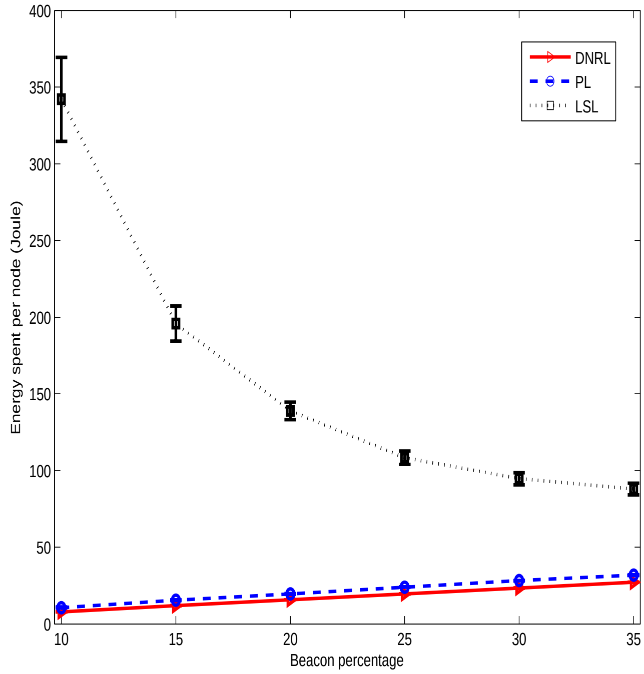

Figure 5.13: Energy consumption per node for the DNRL, PL and LSL schemes for a highly-connected mobile underwater sensor network.

this case, LSL spends at least 200J, which means the underwater nodes will die almost after three months, whereas using DNRL and PL they last a year.

5.5 Evolution of Localization

Monitoring the evolution of localized nodes is important in understanding the required duration of the localization protocol. Localization is usually not the main task of the sensor network but an essential protocol to make the system function properly. Therefore, one needs to know how long it takes to localize a significant portion of the nodes. Note that, the figures in this section can be used to evaluate the delay of the localization techniques. At a first glance, some figures may seem to have inconsistent information with the localization success. For example, usually localization success increases as the number of beacons increases however in the plots of this section higher beacon percentages may seem to localize less nodes. The reason is that the total number of nodes is fixed and it is 250. For example for beacon percentage 30% there are 175 underwater nodes and 75 beacons but in 10% of beacons, there are 225 underwater nodes and 25 beacons. The number of localized nodes are higher

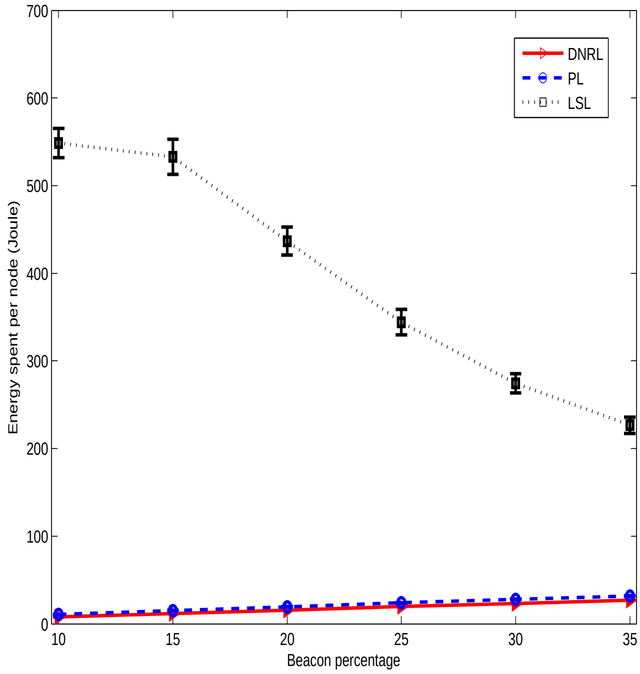

Figure 5.14: Energy consumption per node for the DNRL, PL and LSL schemes for a sparsely-connected mobile underwater sensor network.

in 10% however, the ratio of localized nodes are lower. The reason for keeping the total number of nodes constant is to ensure the same node degree at all beacon percentages.

In Figure 5.15, we give the evolution of the number of localized nodes with respect to time using the PL method for the mobile USN. For beacon percentage of 30%, 1500 seconds are required to localize almost 150 nodes out of 175 (localization success $\simeq$ 88%). For beacon percentage of 20%, 2000 seconds are needed to localize 170 nodes out of 200 (localization success = 85%). For beacon percentage of 10%, 2500 seconds are needed to localize 180 nodes out of 225 nodes (localization success = 80%). Figure 5.15 shows that increasing the number of beacons speed up the localization process. In Figure 5.16, we give the number of localized nodes versus time for the sparsely-connected network for PL. The delays are identical in both scenarios. Recall from Section 5.1 that the localization success is also the same however, low connectivity introduces more errors in PL as discussed in Section 5.3.

In Figure 5.17, we present the number of localized nodes versus time for DNRL for the highly connected mobile USN. In DNRL underwater nodes are localized only by the beacon messages which means the nodes at deep levels wait until a DNR beacon descends and the beacon enters the communication range of the node. Therefore, especially for low beacon percentages such as 10%, the localization delay is 3500 seconds. For the beacon percentage of 20%, it is 3000 seconds. As the beacon percentage increases to 30%, the delay of DNRL decreases to 1000s, leading to a lower value than PL. The performance of DNRL is not affected by the degree of connectivity. The delay is the same for the low connected scenario in Figure 5.18.

In Figure 5.19, we give the evolution of localization using LSL for the highly connected mobile USN. When the beacon percentage is high (30%), a significant portion of the nodes are localized faster than PL and DNRL, i.e. less than 500 seconds. For the beacon percentage of 20% and 10% the localization delays are 1500 and 3000 seconds, respectively.

In Figure 5.20, the localization delay of LSL for the sparsely-connected network is given. A significant amount of nodes are localized after 2000s, for all beacon percentages. LSL is slower than PL and DNRL for sparsely-connected network.

In summary, in highly-connected network, for high beacon percentage, the localization delay of LSL is lower than DNRL and PL. For low beacon percentage, PL has the lowest delay. For sparsely-connected network, LSL has higher delay than DNRL and PL.

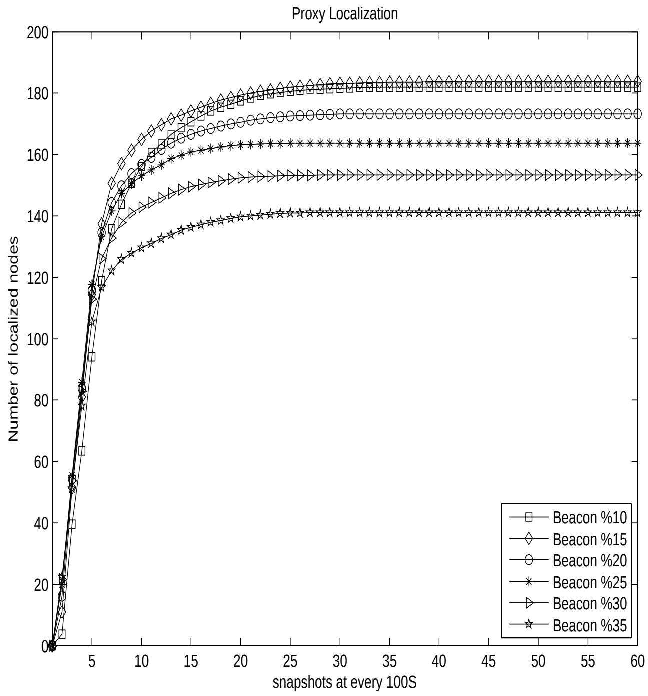

Figure 5.15: Number of localized nodes versus time taken in 100s snapshots for PL method under a highly-connected mobile USN.

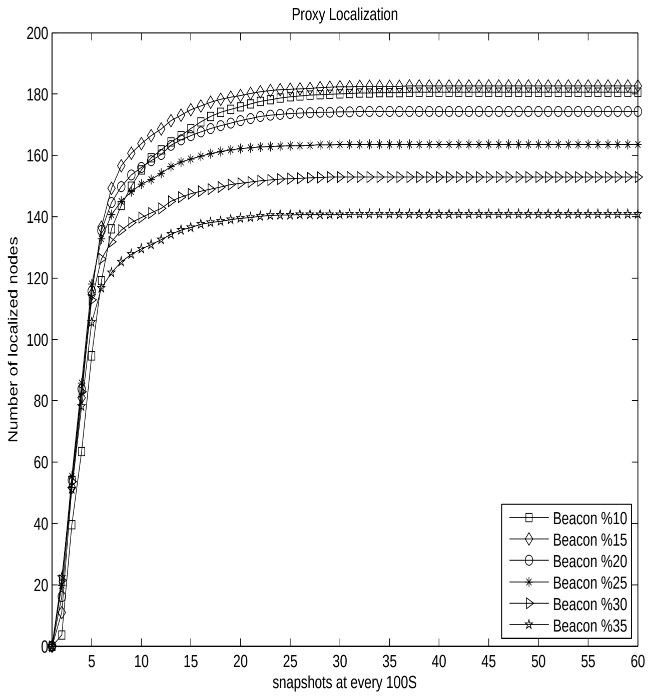

Figure 5.16: Number of localized nodes versus time taken in 100s snapshots for PL method under a sparsely-connected mobile USN.

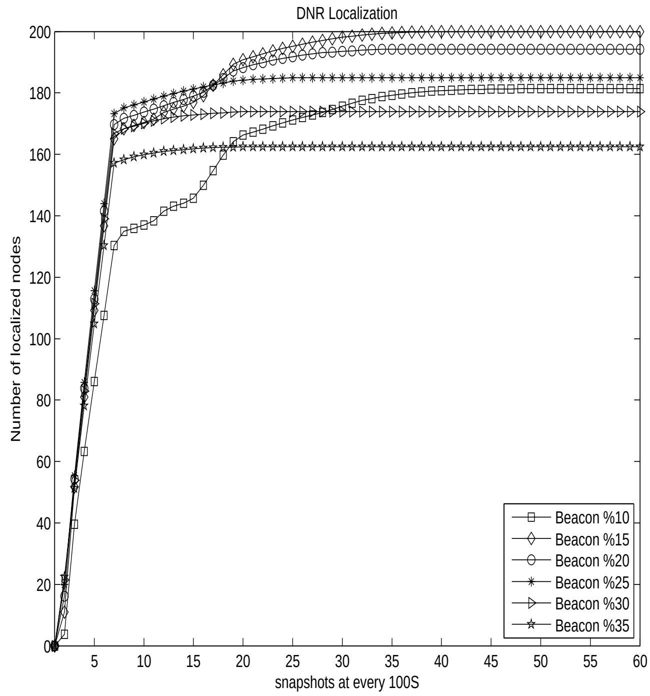

Figure 5.17: Number of localized nodes versus time taken in 100s snapshots for DNR method under a highly-connected mobile USN.

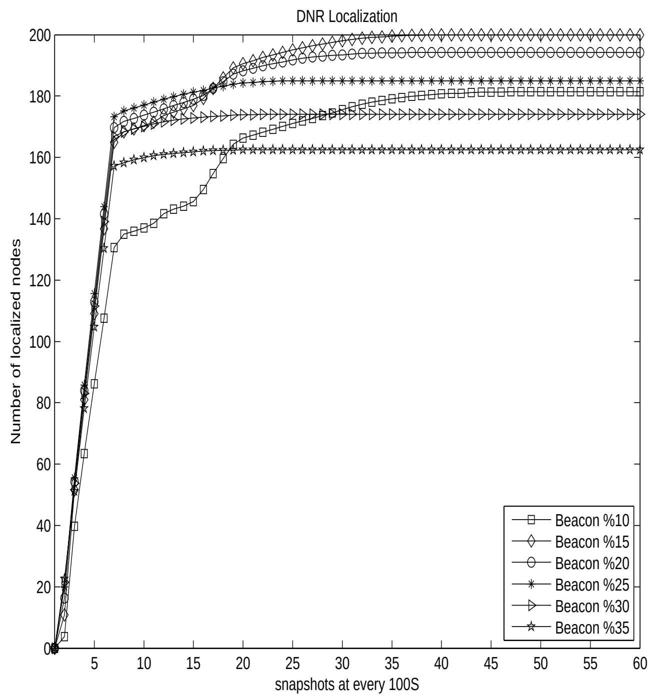

Figure 5.18: Number of localized nodes versus time taken in 100s snapshots for DNR method under a sparsely-connected mobile USN.

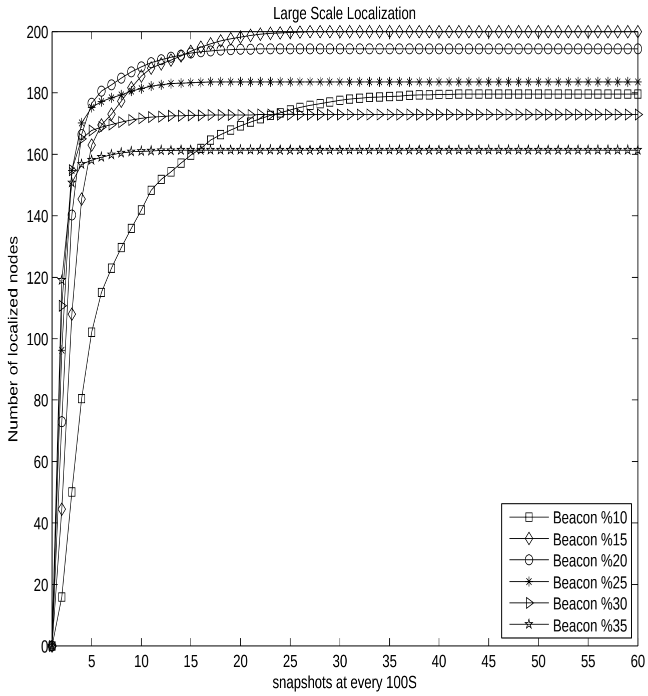

Figure 5.19: Number of localized nodes versus time taken in 100s snapshots for LSL method under a highly-connected mobile USN.

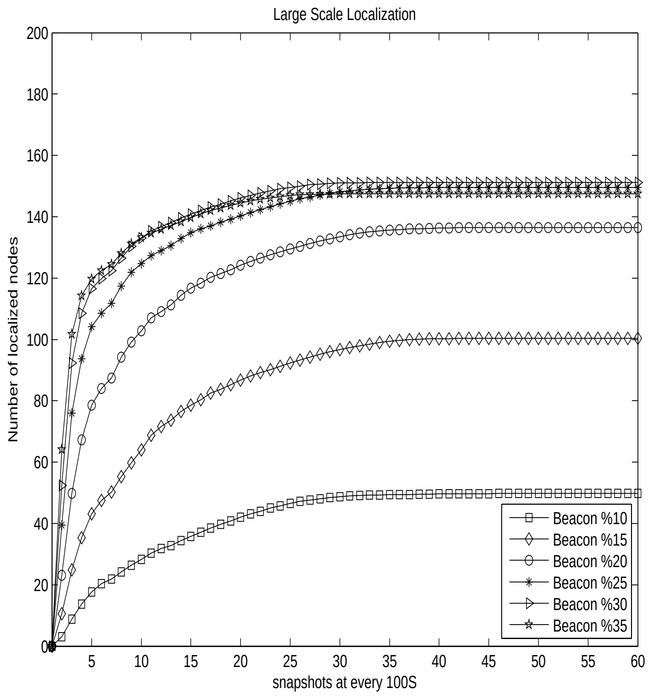

Figure 5.20: Number of localized nodes versus time taken in 100s snapshots for LSL method under a sparsely-connected mobile USN.

6. DATA DELIVERY IN UNDERWATER SENSOR NETWORKS

The design of a data delivery protocol is closely coupled with application requirements. Sensor network applications usually require source to sink communication. In a sensor network architecture, sensor nodes collect data and perform limited processing for data tagging or aggregation. Then, they forward the data to the sink for further processing. Underwater sensor nodes may collect data from their surroundings and transmit them to the sink nodes at certain intervals. On the other hand, underwater network may include gliders, submarines, AUVs, or other equipments that are more complex, powerful and skilled than the ordinary sensor nodes. “DNR” or “Anchor” nodes that are used in the localization process are an example of such hybrid equipments. In a USN, sensor-to-sink, sensor-to-anchor or anchor-to-anchor communication may be required.

In this thesis, we consider data delivery for an underwater mine reconnaissance mission where underwater sensor nodes monitor a coastal region and periodically send data to the sink (see Figure 6.1). In order to provide an initial understanding of the performance of the existing routing protocols for ad hoc networks on a USN we use routing protocols initially considered for ad hoc networks.

Routing protocols for ad hoc networks can be classified as topology-based and position-based protocols. Topology-based protocols depend on the network graph for routing. The proposals for disseminating the topology information are grouped under proactive and reactive (on-demand) approaches. Proactive protocols aim to maintain the routing tables always up-to-date which means the routes are updated even if there is no ongoing communication. This is done by periodic messages. Besides every route change or failure triggers a number of messages. In reactive protocols, routes are calculated when needed, which enables these protocols to establish routes on demand.

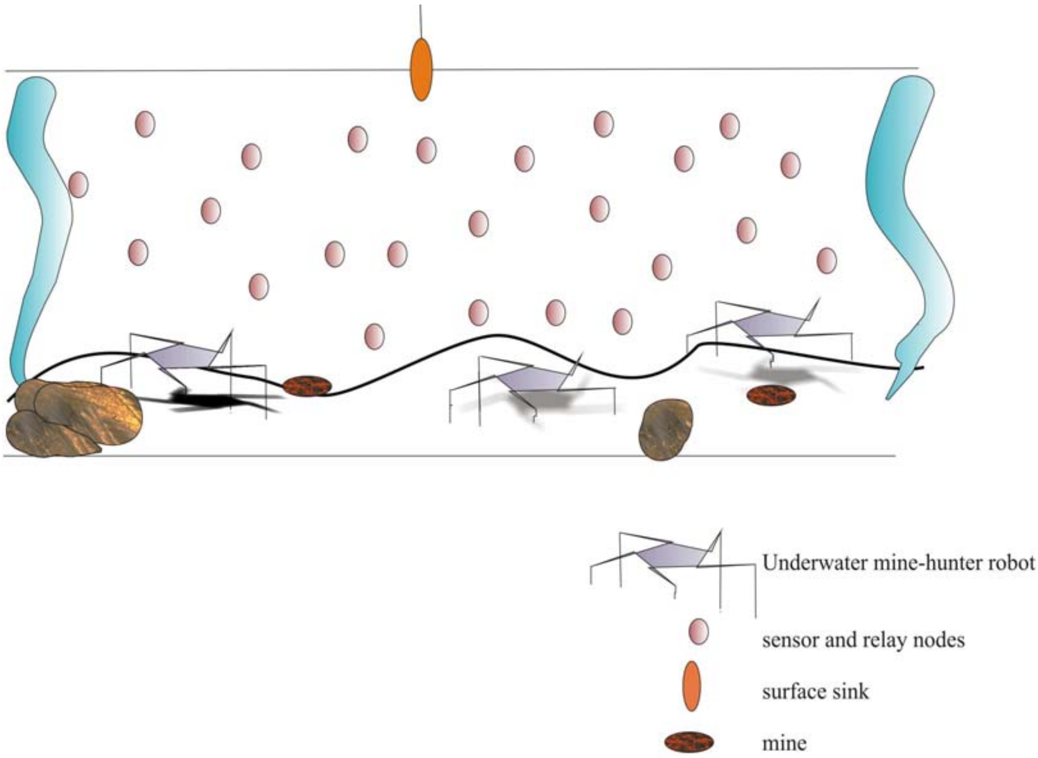

Figure 6.1: Illustration of the data delivery scenario for an underwater mine hunting mission

On the other hand, position-based (or geographic) routing protocols eliminate the need for finding a route before sending a packet [52]. If the positions of all the neighbors and the destination is known, for each packet, a forwarding decision can be made on the way to the destination. The next hop is usually selected so that the distance between this relay node and the destination is minimized. This is a greedy approach and may lead to local minimum problems. A packet may get stuck at a relay where even though the relay is the node minimizing the distance to the destination, it does not have a next hop closer to the destination than itself. The region ahead of such a relay is called a void region and several graph traversing methods have been developed to overcome this problem.

The general approach in evaluating the performance of position-based routing protocols is based on the assumption that the node positions are estimated accurately, i.e., absolute locations of the nodes are available. For a terrestrial ad hoc network, GPS may provide accurate estimates. However, in underwater networking localization is not as accurate as GPS. In this case, the performance of position-based routing protocols under location inaccuracies should be considered [91].

This thesis study employs the current Ad hoc On-demand Distance Vector (AODV) implementation described in [92] as the topology-based protocol. AODV works as follows. When a source has a packet to send it initiates the route discovery process by sending a Route Request (RREQ) packet. RREQ is flooded through the network and once the destination receives a request, it sends a Route Reply (RREP). If there are more packets arriving for the same destination they are buffered until a RREP arrives. During this discovery phase, intermediate nodes learn the routes and store next hops in their routing tables. Since AODV is a distance vector routing protocol, it selects the next hop with minimum hop count if there is more than one candidate. AODV has an aging mechanism to maintain the entries in its routing tables. An entry is "expired" if not used recently. "AODV-ACTIVE-ROUTE-TIMEOUT" is used to control this period. When the age counter expires the entry is deleted to avoid stale entries. In continuous traffic, AODV does not repeat route discovery for each packet. Each time a packet is sent to the destination the age counter is updated so that the entry is not deleted from the routing table. In this case, a route is deleted in case of link failure which is learned through Route Error (RERR) messages. In a route error situation if the "LOCAL-REPAIR" option is selected, then the intermediate node buffers the packets toward the destination with route error and initiates a route discovery. If "LOCAL-REPAIR" is not selected then the packets are dropped and the RERR is sent to predecessor nodes until it reaches the source. In that case, the source initiates a new route discovery. If a node cannot find a path in the route discovery phase for more than maximum "RREQ-RETRIES", the number of retries, it decides that there are no routes to the specific destination. RREQ packets are flooded in an expanding ring. The first RREQ packet has the TTL field set to 1 and this value is incremented by 2 each time. Note that, RREQ packets do not require RTS/CTS exchange because they are broadcast [93]. However, RREP and RERR packets are unicast packets; hence, they require RTS/CTS exchange.

For the location-based protocol, we use a greedy next hop selection algorithm. The packets are forwarded to the relays closest to the destination until there is a void region ahead. The packet is dropped if it meets a void region because graph planarization in 3D is complex and costly. GPSR is one of the most recognized position based routing protocols. GPSR uses graph planarization in 2D to traverse around the void region. Since the USN is 3D, it is not straightforward to use GPSR protocol.

In this chapter, we first compare a table-based routing protocol with a location-based routing protocol in terms of delivery ratio, overhead and average end-to-end delay. We define overhead as the MAC layer RTS/CTS exchange because it represents both the routing protocol packet and data packet overhead. Here, the location-based protocol uses absolute locations. Second, we analyze the performance of the location based protocol when it uses absolute locations and estimated locations that result from the localization protocols. We employ the LSL scheme as the localization protocol, because the mean error values of LSL, DNRL and PL are very close. The overhead of the localization protocol may affect the routing performance, to see this we use the protocol with the highest overhead. Third, we investigate the performance of the location-based protocol with large error values which may be a result of coarse-grained location estimation or mobility.

6.1 Simulation Results

To compare the performance of the data delivery schemes, we again use the Qualnet simulator. The acoustic physical layer is implemented with a 50Kbps data rate. We use the two ray path loss model. The speed of sound is chosen to be 1513m/s. We randomly distribute 50 nodes in a (150, 150, 300) volume and set the transmission range to 80m. The average node degree is 14. The traffic generating sources are Constant Bit Rate (CBR) traffic. The packet interarrival times are 15, 10, 5 minutes and 50, 40, 30, 20, 10 seconds. The queue size of the nodes is 50KB and the packet size is 78B including the payload and the headers. Considering that the Aquafleck nodes [38] have 512kBytes of flash memory for data storage, 50KB of buffer space is feasible. Moreover, this queue size ensures that packets are not dropped due to overflow at low interarrival values. The number of sources are 40 among 50 nodes, sparing 10 nodes to be the anchors during the simulations including localization methods, making a beacon percentage of 20%. We use a single sink node placed on the surface. The average hop count is measured to be 3, and the average internodal distance is 60m.

At the MAC layer, we use the MACA protocol that employs RTS/CTS pairs. In underwater acoustic networks, transmission of data packets takes longer than in radio-based ad hoc networks due to longer propagation delays. In this case, the time interval during which possible contentions could occur increases. We modify the conventional MACA protocol to back off for a longer time. This decreases the contentions and increases the packet delivery ratio but increases the end-to-end delay.

For the topology-based protocol we use the IETF draft implementation of AODV [92]. In the IETF draft the configurable parameters and their recommended values are given. We use timer values longer than recommended for RF communication. We set AODV-ACTIVE-ROUTE-TIMEOUT to 50s. We also set RREQ-RETRIES to 5 and allow local repair. AODV buffers all the packets destined to a node after starting a route discovery for that destination. We keep these buffers large enough so that AODV does not drop any packets (50KB). All the packets (control and data), are kept at interface queues with priorities. Routing packets are given the highest priority. For the location-based protocol, since we consider a stationary network, we keep the beacon sending frequency low. The beacon update interval is selected to be 600s.

We compare the performance of a topology and location-based routing protocol in terms of delivery ratio, overhead and end-to-end delay. We consider a stationary USN. We give the average values of 10 simulation runs. Simulations last for 500 minutes. The first 30 minutes are spared for warm-up and traffic generation ends before the last 50 minutes.

6.2 Topology-based and Location-based Routing

In Figure 6.2, we compare the delivery ratio of a topology-based and location-based routing protocol. The interarrival times are 900, 300, 100, 50, 40, 30, 20, 10 seconds. The topology-based routing protocol delivers all the generated packets to the sink under low rates (interarrival times larger than 40s) where the interarrival times are above 30s. Starting from the interarrival time of 20s, the delivery ratio of the topology-based protocol decreases. For the interarrival time of 10s and the delivery ratio is less than 0.5. At interarrival times above 20s, location-based routing protocol has lower delivery ratio than topology-based routing protocol. There are two reasons for packet loss. One is the inefficiency of the routing protocol. The other is the queue overflow. In Figure 6.3, we give the number of packets dropped due to routing protocol inefficiency divided by the number of sent packets. The inefficiency

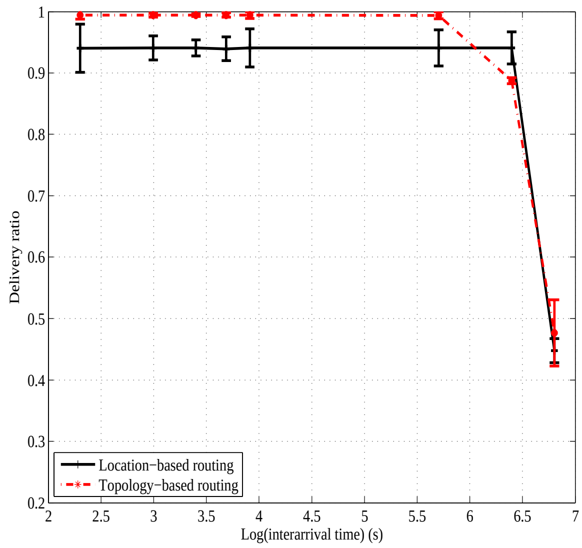

Figure 6.2: Delivery ratio of a topology-based routing protocol and a location-based routing protocol.

is in general due to unavailable neighbors in topology-based protocols and geographic voids in location-based protocols. As we observe from Figure 6.3, for the same topology, the location-based protocol drops more packets. In fact, we implement a greedy location-based approach where a packet is dropped when it meets a void. More sophisticated methods are available for void traversal however they work in 2D. If void handling techniques are used, the location-based protocol may have a higher delivery ratio.

In Figure 6.4, the ratio of packets dropped due to queue overflow is given. The drop ratio increases at interarrival time 10s. We detailed our analysis on simulation traces and observed that several nodes forward the significant portion of the traffic. In Figure 6.4, the topology-based routing protocol seems to drop more packets than the location-based protocol however, the location-based protocol drops some portion of the packets due to voids and this leaves free space on the queues for the other packets in the network. In Figure 6.5, we give the topology of the nodes that are on the most preferred paths. The sink floats on the surface (level 0) and the other nodes are under the water therefore the z coordinate is denoted by minus sign. The nodes on the most preferred path are 2, 13, 22, 25, 38 and 45. Note that, those nodes topologically lay at the cylindrical region below the sink. In a 2D sensor network, the nodes in the ring around the sink forward the large number of packets. In the 3D underwater

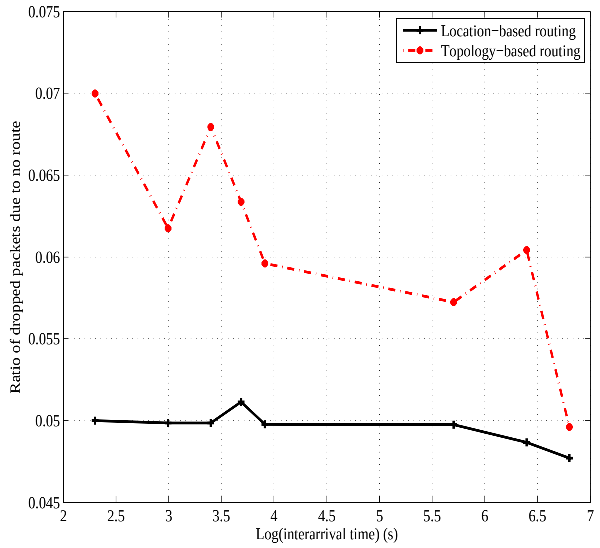

Figure 6.3: Ratio of dropped packets due to the inefficiency of the routing protocol for a topology-based routing protocol and a location-based routing protocol.

environment this becomes a cylindrical region under the sink when the sink is floating at the surface. We give the queue lengths for the nodes on the most preferred path in Figure 6.6. The queues of these nodes overflow while the queues of other nodes stay at short queue lengths. We also investigate the self-similarity of traffic at an heavily loaded node. The results are given in Appendix B.

The performance degradation at short interarrivals times is also due to the MAC layer protocol. We use MACA, where RTS/CTS exchange is required. MACA is useful for avoiding hidden terminal problem and simultaneous transmissions. However in underwater it consumes bandwidth and adversely affects the data delivery. A more energy-efficient MAC may be used, however, MAC layer protocols for USNs are in the development phase. Proposing a MAC solution is out of the scope of this thesis, therefore, we use a conventional technique. In Figure 6.7, we give the number of RTS/CTS packets divided by total number of sent packets. This represents the overhead due to the protocol packets and data packets. As the packet generation rate increase, the effect of MAC becomes more visible. The ratio of RTS/CTS exchange increases with unsuccessful delivery, in return this increases overhead, consumes bandwidth and decreases the delivery ratio.

The average end-to-end delay for the protocols are given in Figure 6.8. The average end-to-end delay should be interpreted together with the number of packets generated.

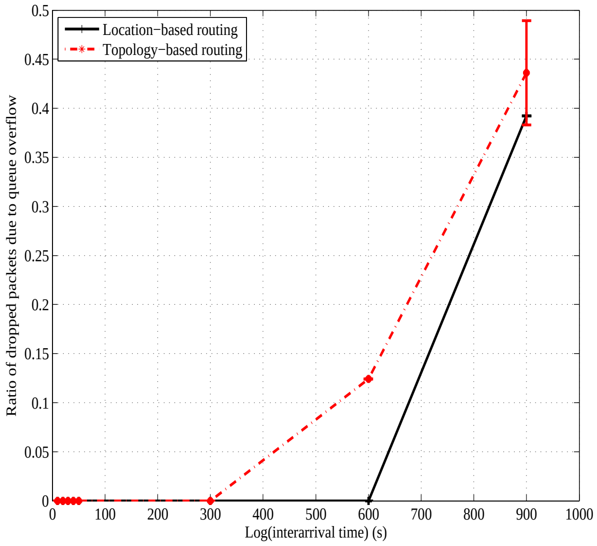

Figure 6.4: Ratio of dropped packets due queue overflow for a topology-based routing protocol and a location-based routing protocol.

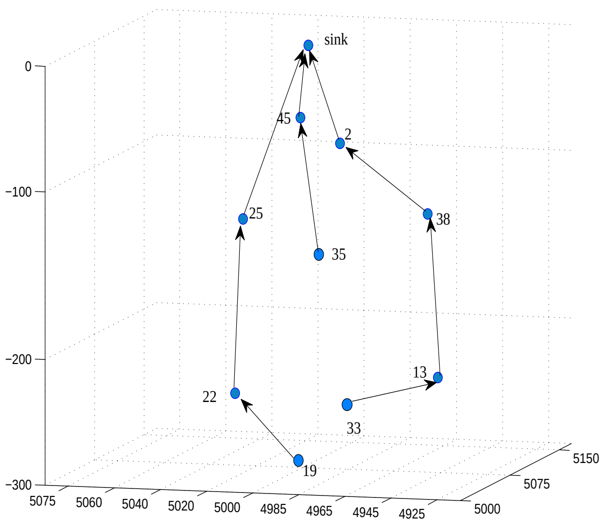

Figure 6.5: The nodes on the most preferred path and illustration of several source-destination paths.

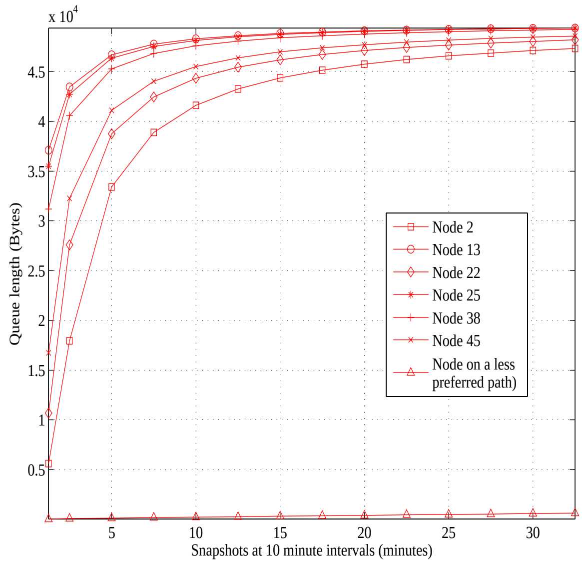

Figure 6.6: Queue lengths of the nodes on the most preferred paths.

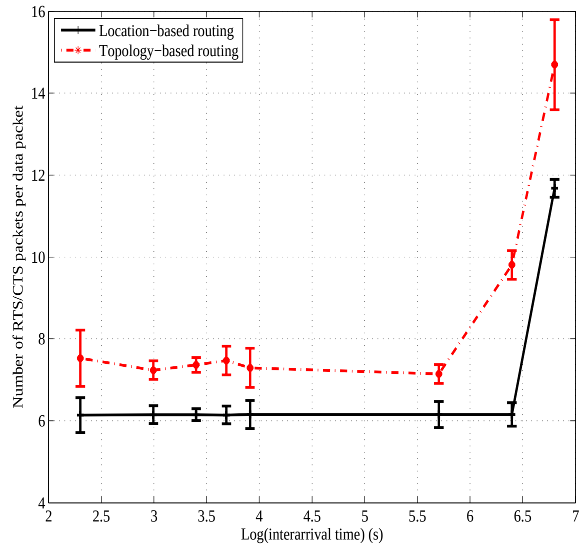

Figure 6.7: RTS/CTS exchange per one data packet for a topology-based routing protocol and a location-based routing protocol.

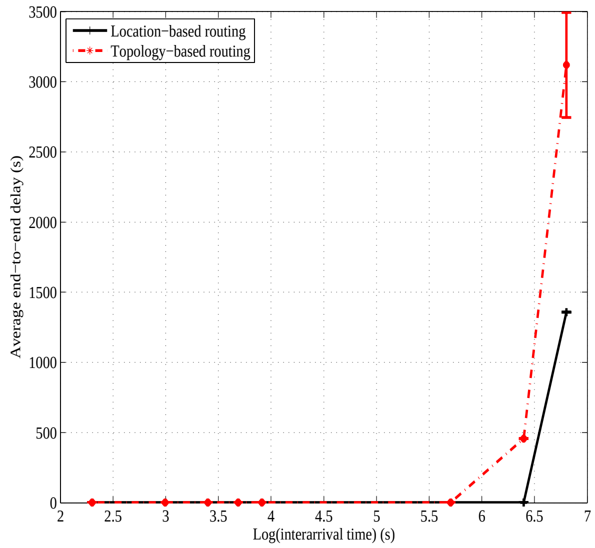

Figure 6.8: Average end-to-end delay for a topology-based routing protocol and a location-based routing protocol.

At low interarrival times more packets are generated and as expected the end-to-end delay is long. It is convenient to compare the overhead and the average end-to-end delay of the two routing protocols when their delivery ratios are close. The packets that are dropped at the first hops leave space for the packets on the further hops, decreasing overhead and delay. At interarrival time 10s, they deliver around 0.47 of the packets, in this case, the topology-based protocol has higher overhead and longer delay.

6.3 Location-based Routing with Estimated Locations

In the previous section, location-based routing used the absolute locations of the nodes. However, in practice, absolute location may not be available and the location estimated by localization methods are used. The estimated locations naturally include errors and each localization method introduces some error. In fact, the accuracy level of the localization method is also coupled with the application. Some applications may require precise localization whereas some need to know only the whereabouts of the sensor nodes. In this sense, localization protocols bare various accuracy values. The localization protocols introduced in this thesis have similar mean error values, all of which are below 10% of the range. DNRL, PL and LSL have similar mean error, and LSL additionally produces more overhead than the other methods. Therefore, we only analyze the impact of LSL on data delivery. In Figure 6.9, we give the delivery ratio of

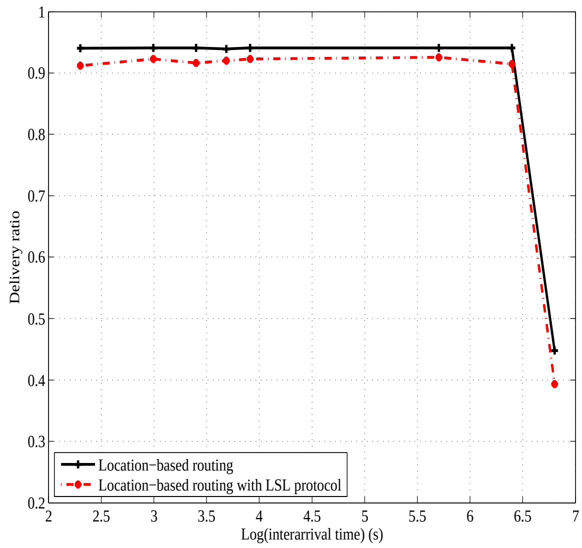

Figure 6.9: Delivery ratio of a location-based routing protocol with absolute locations and a location-based routing protocol that uses LSL scheme.

the location-based protocol using absolute locations and locations estimated by LSL. The delivery ratio slightly decreases when LSL is used.

In Figure 6.10, we give the ratio of packets dropped due to voids. Although the topologies are the same, erroneous location information decreases the performance of the greedy protocol. The location-based routing protocol establishes a sanity check on the distance measurements between its neighbors and itself. When a node receives a beacon from a neighbor, it calculates the distance. If it exceeds the range, the node decides that the neighbor has inaccurate location information. This neighbor is marked as “unavailable” in the routing table of the protocol. In next hop selection, location error affects the number of packets dropped due to unavailable nodes.

In Figure 6.11, we give the packet drop ratio due to buffer overflow. The overhead of LSL does not affect the drop rate at the queues. If underwater nodes had very limited buffer space, the number of messages generated by LSL could affect the drop rate. However, we assume 50KB of buffer size, which is feasible for current underwater sensor nodes.

The effect of the overhead of LSL is observed in Figure 6.12. The ratio of RTS/CTS exchange increases. Localization packets are broadcast and do not require RTS/CTS exchange; however, they increase contention and, in return, overhead.

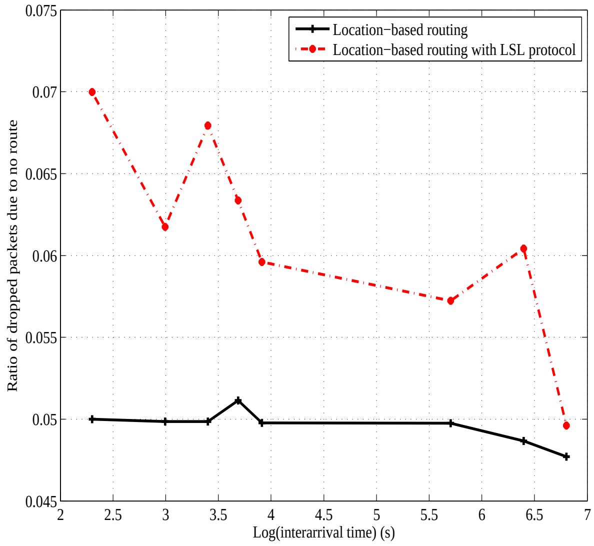

Figure 6.10: Ratio of dropped packets due to the inefficiency of the routing protocol for location-based routing protocol with absolute locations and a location-based routing protocol that uses LSL scheme.

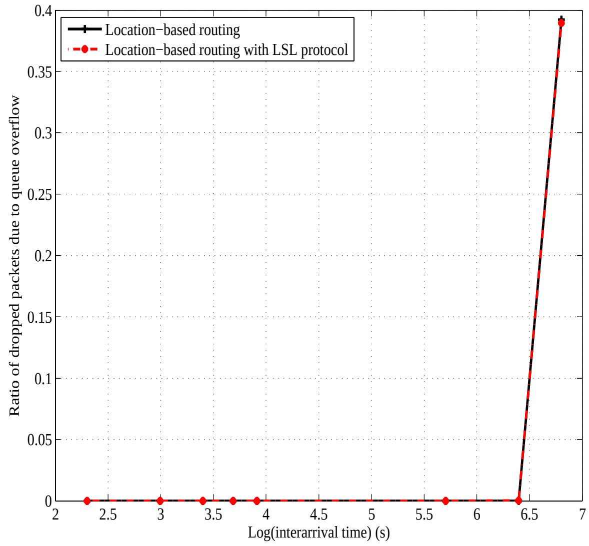

Figure 6.11: Ratio of dropped packets due to queue overflow for location-based routing protocol with absolute locations and a location-based routing protocol that uses LSL scheme.

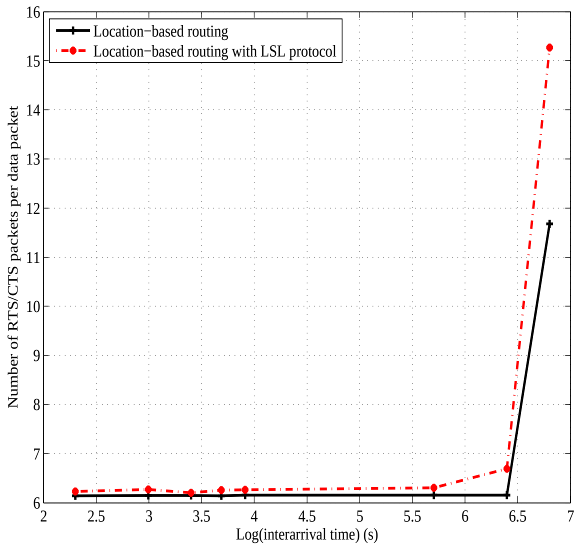

Figure 6.12: RTS/CTS exchange per one data packet for location-based routing protocol with absolute locations and a location-based routing protocol that uses LSL scheme.

In Figure 6.13, we give the average end-to-end delay. The end-to-end delay increases when LSL is used. LSL injects additional packets and this increases the average waiting time in queue.

6.4 Location-based Protocol under Low Accuracy

Localization accuracy may decrease when coarse-grained location estimation methods are used or when the network is mobile. In this section, we analyze the impact of accuracy on the performance of the location-based routing protocol. We keep the overhead the same as in the previous section and add intentional location errors that correspond to 20%, 30%, 40% and 50% of the range. This means that the (x, y) coordinates have mean errors of 16m, 24m, 32m and 40m. In Figure 6.14, we give the delivery ratios for the location-based protocol under various mean error values. Delivery ratio decreases as the mean error increase. However, at the interarrival time 10s, all mean error values lead to delivery ratios around 0.35. This is the lowest delivery ratio because one third of the nodes are at one hop distance to the sink. The location of the sink is absolute since it can be received from GPS. These one hop neighbors can deliver their packets to the sink but the nodes that are multiple-hops away face high drop rates due to wrong location estimates. The number of packets dropped due to no route is given in Figure 6.15. For high error values more packets

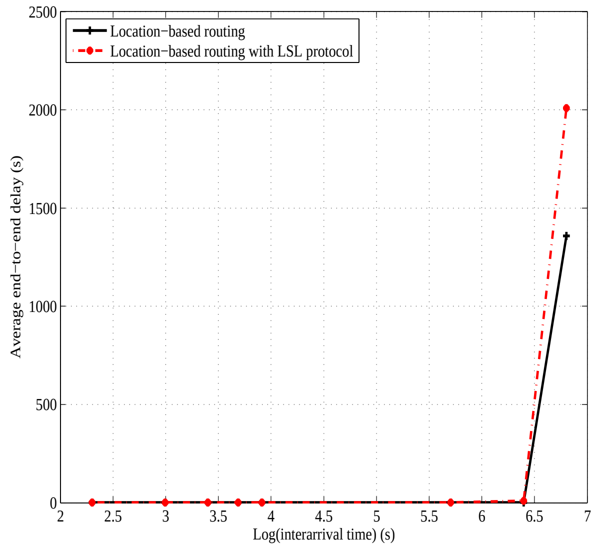

Figure 6.13: Average end-to-end delay for location-based routing protocol with absolute locations and a location-based routing protocol that uses LSL scheme.

are dropped due to incorrect location information. In fact, number of dropped packets increases with shorter interarrival times however the ratio decreases due to the increasing number of sent packets. The ratio of packets dropped due to buffer overflow is given in Figure 6.16. For high mean error values, fewer packets are dropped at the buffers because a significant portion has already been dropped due to routing voids. The overhead is related with the number of sent packets therefore it is not affected by errors, hence we do not give the RTS/CTS exchange graph.

The average end-to-end delay is given in Figure 6.17. Since the number of packets delivered decrease when the error is high, the end-to-end delay decreases at higher error values, as well.

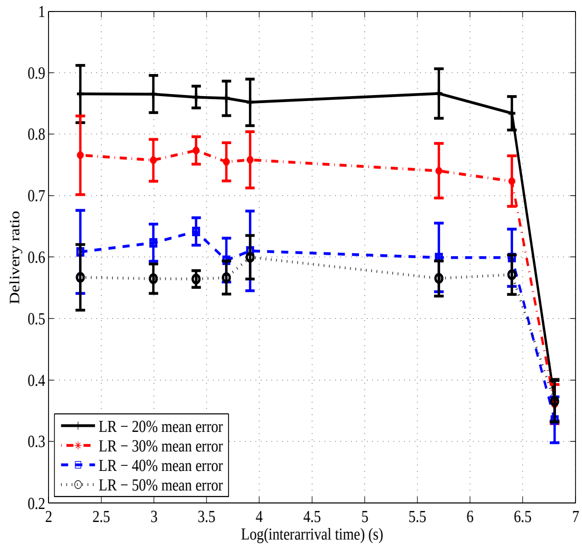

Figure 6.14: Delivery ratio of a location-based routing protocol under large mean error values.

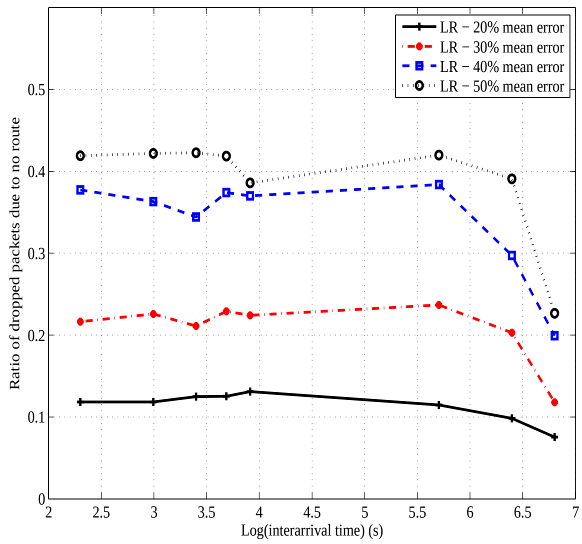

Figure 6.15: Ratio of dropped packets due to the inefficiency of the routing protocol for a location-based routing protocol under large mean error values.

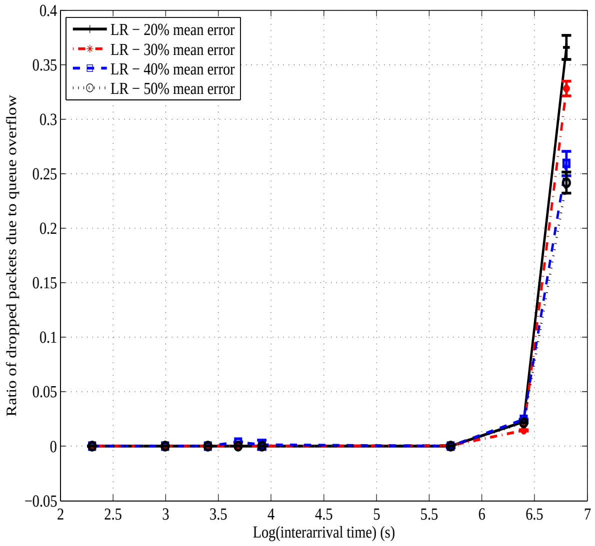

Figure 6.16: Ratio of dropped packets due to queue overflow for a location-based routing protocol under large mean error values.

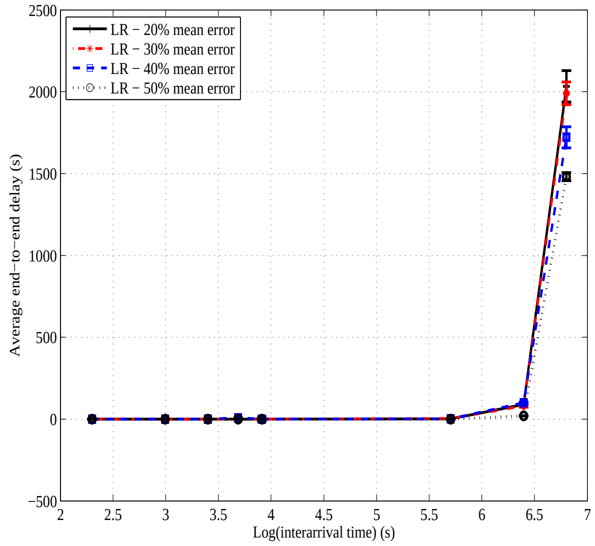

Figure 6.17: Average end-to-end delay for a location-based routing protocol under large mean error values.

7. CONCLUSION

Underwater networking is a challenging environment with promising new application areas. USNs can improve ocean exploration, allowing a list of new applications that are presently not possible or have high cost, including:

* ecological applications
    - pollution and water quality monitoring
    - ocean temperature and conductivity monitoring
    - coral reef observation
* public safety applications
    - earthquake and tsunami forecasting
    - detection of chemical spill dangerous to human life
* military underwater surveillance applications
    - submarine detection
    - mine reconnaissance
* industrial applications
    - offshore oil platform monitoring

These next generation oceanographic applications require networking among the underwater equipments. RF and optical signals cannot travel far in underwater, whereas acoustic signals are able to travel up to several kilometers. Nevertheless, bandwidths of these long-distance links are not adequate for data transmission. Shorter inter node distances are preferred to increase the bandwidth of USNs. However, still acoustic links have lower bandwidths, longer delays and higher bit error rate than terrestrial RF, and they are exposed to multipath and fading effects. These inherent problems demand novel solutions at every layer of the protocol stack and sometimes cross layer solutions. Therefore USNs have recently attracted the networking community. In USN literature, localization, synchronization, medium access, routing and transport layer protocols have been addressed. In general, centralized solutions for stationary USNs dominate the research efforts. There are few works that consider mobile USNs and in general, they assume either random waypoint mobility or group mobility which do not reflect the motion pattern in an oceanographic environment.

In this thesis, we contribute to a mobility model for underwater sensor networks. The detailed parameter verification and effects of this model on coverage and connectivity have been studied in [84] and the details are out of the scope of this thesis. We use the MCM-SE model to evaluate the performance of our techniques for a mobile network.

In this thesis, we focus on localization and data delivery. We propose two localization algorithms and compare their performance with a recognized technique from the literature. Our proposals are Dive aNd Rise Localization (DNRL) and Proxy Localization (PL). The reason for comparing DNRL and PL with Large Scale Localization (LSL) is that they aim to solve the localization problem for similar a USN architecture, which is large-scale, 3D and untethered. We show that DNRL outperforms PL and LSL in mobile scenarios. It has high localization success, low error, low energy consumption and low overhead. Its disadvantage is that, it introduces longer delay than the other methods. This is due to the diving velocity of the DNR beacons. When propelled vehicles are used, faster localization could be possible, however, in this case, the cost of DNR design will increase, and energy consumption for the mechanical motion would be another issue. LSL has unaffordable overhead and energy consumption in the mobile network. In the stationary scenarios, DNRL is advantageous in the sense of energy efficiency and accuracy, while LSL can be preferred for its higher delivery ratio. In a stationary network, localization does not have to be done frequently and the energy consumption of LSL may be kept limited. In a stationary network, PL has moderate localization success, affordable overhead, comparable error and it establishes localization faster than the other two methods.

However, its accuracy is very low for the mobile network. The accuracy of PL can be improved by more frequent aging however this results in more energy consumption.

In this thesis, we also study data delivery in stationary underwater sensor networks. Localization is can be useful in data tagging however, once it is retrieved it can be used in a location-based routing protocols. Therefore, we analyze the performance of a simple, greedy, location-based routing protocol in terms of delivery ratio, overhead and average end-to-end delay. To provide a comparison we also employ a reactive topology-based routing protocol. We show that the location-based routing protocol has lower delivery ratio than the topology-based protocol due to geographic voids. Although the average node degree is relatively high compared to that in terrestrial sensor studies, it is still possible to have void regions in the 3D network. Using a dense network may improve the delivery ratio at an additional cost. A better solution is using void avoidance techniques. Traversing around the void region using graph planarization has been well established in 2D. However, extending the graph planarization to 3D is not straightforward. Underwater networking demands novel solutions on this topic which can be a future direction. In our studies, we show that in a 3D underwater network, the nodes that float below the cylindrical region under the sink are the busiest nodes. They perform most of the data forwarding, therefore, packets are dropped at high packet rates. The delivery ratio of the location-based routing protocol is affected by the consistency of the location information. It is possible to group localization protocols as fine and coarse-grained. Although application requirements define the level of accuracy, localization protocols proposed in this thesis have mean error ratios below 10% and can be considered fine-grained. When the location estimates of fine-grained localization protocols are used, the delivery ratio decreases slightly. However, when coarse-grained localization methods are used or when nodes are untethered and move with currents, the mean error ratio increases and as a result the delivery ratio decreases. The reason for the low delivery ratio is the occurrence of virtual voids due to wrong location information.

As a future work, we plan to study data delivery characteristics in various topologies.

We have observed that geographic voids cause packet loss. USNs demand energy-efficient, 3D and loop-free void handling techniques. Future work to extend this thesis may be developing novel void handling or avoidance techniques.

Moreover, we observed that medium access protocols affect the performance of higher layer protocols, therefore a robust, energy-efficient MAC design for underwater sensor networks is significant. A cross-layer approach combining the localization plane with medium access and network layer can be a future study.

REFERENCES

[1] **Heidemann, J.**, **Ye, W.**, **Wills, J.**, **Syed, A. and Li, Y.**, 2006. Research challenges and applications for underwater sensor networking, IEEE Wireless Communications and Networking Conference (WCNC), Las Vegas, USA, April 3-6.

[2] **Syed, A. and Heidemann, J.**, 2006. Time synchronization for high latency acoustic networks, Proc. of the IEEE Infocom, Barcelona, Spain, April.

[3] **Erol, M.**, **Vieira, L. and Gerla, M.**, 2007. Localization with Dive'N'Rise (DNR) beacons for underwater acoustic sensor networks, Proc. of the second workshop on Underwater networks (WuWNet), Montreal, Quebec, Canada, pp. 97–100.

[4] **Erol, M.**, **Vieira, L.**, **Caruso, A.**, **Paparella, F.**, **Gerla, M. and Oktug, S.**, 2008. Multi Stage Underwater Sensor Localization using Mobile Beacons, Proc. of: The Second International Workshop on Under Water Sensors and Systems workshop (in conj. with SENSORCOMM08, Cap Esterel, France, August 25-31.

[5] **Zhou, Z.**, **Cui, J. and Zhou, S.**, 2007. Localization for large-scale underwater sensor networks, In Proceedings of IFIP Networking'07, Atlanta, Georgia, USA, May, pp. 108–119.

[6] **Headrick, R. and Freitag, L.**, 2009. Growth of underwater communication technology in the U.S. Navy, *Communications Magazine, IEEE*, 80–82.

[7] **Hightower, J. and Borriello, G.**, 2001. Location Sensing Techniques, UW CSE 01-07-01, Tech. Rep. University of Washington, Department of Computer Science and Engineering, Seattle, WA.

[8] **Savvides, A.**, **Han, C.C. and Strivastava, M.B.**, 2001. Dynamic fine-grained localization in ad-hoc networks of sensors, MobiCom '01, Rome, Italy, pp. 166–179.

[9] **Kong, J.**, **Cui, J.**, **Wu, D. and Gerla, M.**, 2005. Building underwater ad-hoc networks and sensor networks for large scale real-time aquatic applications, IEEE MILCOM, Atlantic City, NJ, USA.

[10] **Xie, P.**, **Cui, J. and Lao, L.**, 2006. VBF: Vector-Based Forwarding Protocol for Underwater Sensor Networks, In Proc. of IFIP Networking'06, Portugual.

[11] **Capkun, S.**, **Hamdi, M. and Hubaux, J.P.**, 2001. GPS-free positioning in mobile ad-hoc networks, Proc. of the 34th Annual Hawaii Int. Conference on System Sciences (HICSS-34), Maui, Hawaii,USA.

[12] **Caruso, A.**, **Chessa, S.**, **De, S. and Urpi, A.**, 2005. GPS-free coordinate assignment and routing in wireless sensor networks, Proc. of INFOCOM 2005, Miami, USA, pp. 150–160.

[13] **Chandrasekhar, V.**, **Seah, W.K.**, **Choo, Y.S. and Ee, H.V.**, 2006. Localization in underwater sensor networks: survey and challenges, Proc. of the first workshop on Underwater networks (WuWNet), Los Angeles, CA, USA, pp. 33–40.

[14] **Savarese, C.**, **Rabaey, J.M. and Langendoen, K.**, 2002. Robust positioning algorithms for distributed ad-hoc wireless sensor networks, Proc. of 2002 USENIX Annual Technical Conference, Monterey, CA, USA, pp. 317–327.

[15] **He, T.**, **Huang, C.**, **Blum, B.M.**, **Stankovic, J.A. and Abdelzaher, T.**, 2003. Range-free localization schemes for large scale sensor networks, MobiCom '03, San Diego, CA, USA, pp. 81–95.

[16] **Bulusu, N.**, **Heidemann, J. and Estrin, D.**, 2000. Gps-less low cost outdoor localization for very small devices, *IEEE Personal Communications Magazine,* October, **7(5)**, 28–34.

[17] **Savvides, A.**, **Park, H. and Srivastava, M.B.**, 2002. The bits and flops of the n-hop multilateration primitive for node localization problems, WSNA '02: Proc. of the 1st ACM Int. workshop on Wireless sensor networks and applications, Atlanta, Georgia, USA, pp. 112–121.

[18] **Tilak, S.**, **Kolar, V.**, **Abu-Ghazaleh, N.B. and Kang, K.D.**, 2005. Dynamic Localization Control for Mobile Sensor Networks, IEEE Int. Workshop on Strategies for Energy Efficiency in Ad Hoc and Sensor Networks, Phoenix, AZ, USA.

[19] **Hu, L. and Evans, D.**, 2004. Localization for mobile sensor networks, MobiCom '04, Philadelphia, PA, USA, pp. 45–57.

[20] **Url-1**, *<http://www.dosits.org/gallery/tech/ooct/sofar1.htm>, accessed on 20 January 2009*.

[21] **Collin, L.**, **Azou, S.**, **Yao, K. and Burel, G.**, 2000. On Spatial Uncertainty In a Surface Long Baseline Positioning System, Proc. of the 5^{th} European Conference on Underwater Acoustics (ECUA), Lyon, France.

[22] **Gould, W. and Turton, J.**, 2006. Argo – Sounding the Oceans, *Weather,* **61(1)**, 17–21.

[23] **Url-2**, *<http://www.argo.ucsd.edu/>, accessed on 19 December 2008*.

[24] **Ohlmann, J.C.**, **White, P.F.**, **Sybrandy, A.L. and Niiler, P.P.**, 2005. GPS-cellular drifter technology for coastal ocean observing systems, *J. of Atmospheric and Oceanic Technology,* **22(9)**, 1381–1388.

[25] **Jaffe, J.**, **Glatts, R.**, **Schurgers, C.**, **Mirza, D.**, **Franks, P.**, **Roberts, P. and Simonet, F.**, 2007. AUE: An Autonomous Float for Monitoring the Upper Water Column, Oceans'07, Aberdeen, Scotland, June.

[26] **Url-3**, *<www.neptunecanada.ca/about/index.html>, accessed on 19 December 2008*.

[27] **Url-4**, *<http://www.mbari.org/mars/>, accessed on 14 February 2009*.

[28] **Mitsuzawa, K.**, **Iwase, R.**, **Otsuka, R.**, **Hirata, K. and Mikada, H.**, 2004. Long-term deep current measurements by JAMSTEC cabled observatories, Proc. of OCEANS ’04. MTTS/IEEE TECHNO-OCEAN, November, volume 4, pp. 2206–2210.

[29] **Rice, J.A.**, 2007. US navy seaweb development, WuWNet ’07: Proceedings of the second workshop on Underwater networks, Montreal, Quebec, Canada, pp. 3–4.

[30] **Pompili, D.**, **Melodia, T. and Akyildiz, I.F.**, 2006. A Resilient Routing Algorithm for Long-term Applications in Underwater Sensor Networks, Proceedings of Med-Hoc-Net’06, Lipari, Italy, june.

[31] **Partan, J.**, **Kurose, J. and Levine, B.N.**, 2006. A survey of practical issues in underwater networks, Proc. of the first workshop on Underwater networks (WuWNet), Los Angeles, CA, USA, pp. 17–24.

[32] **Stojanovic, M. and Preisig, J.**, 2009. Underwater acoustic communication channels: Propagation models and statistical characterization, *Communications Magazine, IEEE*, 84–89.

[33] **Kilfoyle, D.B. and Baggeroer, A.B.**, 2000. The State of the Art in Underwater Acoustic Telemetry, *IEEE J. of Oceanic Enginnering*, **25(1)**, 4–27.

[34] **Url-5**, *<http://acomms.whoi.edu/micromodem/>, accessed on 16 May 2009*.

[35] **Url-6**, *<http://www.dspcomm.com/>, accessed on 20 January 2009*.

[36] **Url-7**, *<http://www.link-quest.com/html/uwm2200.htm>, accessed on 12 February 2009*.

[37] **Url-8**, *<http://www.benthos.com/>, accessed on 22 December 2009*.

[38] **Vasilescu, I.**, **Kotay, K.**, **Rus, D.**, **Dunbabin, M. and Corke, P.**, 2005. Data collection, storage, and retrieval with an underwater sensor network, Proc. of the 3_{rd} Int. Conf. on embedded networked sensor systems (SenSys), San Diego, CA, USA, pp. 154–165.

[39] **Pompili, D. and Akyildiz, I.**, 2009. Overview of networking protocols for underwater wireless communications, *Communications Magazine, IEEE*, 97–102.

[40] **Pompili, D. and Melodia, T.**, 2005. Three-dimensional routing in underwater acoustic sensor networks, PE-WASUN ’05: Proc. of the 2nd ACM Int. workshop on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks, Montreal, Quebec, Canada, pp. 214–221.

[41] **Park, M.K. and Rodoplu, V.**, 2007. UWAN-MAC: An Energy-efficient MAC Protocol for Underwater Acoustic Wireless Networks, *IEEE/MTS Journal of Oceanic Engineering*, january, **32(3)**, 710–720.

[42] **Tateson, J.**, **Roadknight, C.**, **Gonzalez, A.**, **Khan, T.**, **Fitz, S.**, **Henning, I.**, **Boyd, N.**, **Vincent, C. and Marshall, I.**, 2005. Real World Issues in Deploying a Wireless Sensor Network for Oceanography, Workshop on Real-World Wireless Sensor Networks (REALWSN'05), Stockholm, Sweden.

[43] **Voigt, T.**, **Osterlind, F.**, **Finne, N.**, **Tsiftes, N.**, **He, Z.**, **Eriksson, J.**, **Dunkels, A.**, **Bamstedt, U.**, **Schiller, J. and Hjort, K.**, 2007. Sensor Networking in Aquatic Environments - Experiences and New Challenges, LCN '07: Proceedings of the 32nd IEEE Conference on Local Computer Networks, IEEE Computer Society, Washington, DC, USA, pp. 793–798.

[44] **Othman, A.K.**, **Adams, A.E. and Tsimenidis, C.C.**, 2006. Node Discovery Protocol and Localization for Distributed Underwater Acoustic Networks, Proc. of the Adv. Int. Conf. on Telecommunications, Internet, Web Applications and Services (AICT-ICIW), Washington, DC, USA, p. 93.

[45] **Chandrasekhar, V. and Seah, W.**, 2006. An Area Localization Scheme for Underwater Sensor Networks, OCEANS 2006 - Asia Pacific, May, pp. 1–8.

[46] **Mirza, D. and Schurgers, C.**, 2008. Motion-aware self-localization for underwater networks, WuWNeT '08: Proceedings of the third ACM international workshop on Wireless network testbeds, experimental evaluation and characterization, San Francisco, California, USA, pp. 51–58.

[47] **Erol, M.**, **Vieira, L. and Gerla, M.**, 2007. AUV-Aided Localization for Underwater Sensor Networks, Int. Conf. on Wireless Algorithms, Systems and Applications (WASA), Chicago, IL, US.

[48] **Z. Zhou, J.C. and Bagtzoglou, A.**, 2007. Scalable Localization with Mobility Prediction for Underwater Sensor Networks, Proc. of the second workshop on Underwater networks (WuWNet), Montreal, Quebec, Canada.

[49] **Erol, M.**, **Oktug, S.**, **Vieira, L. and Gerla, M.**, 2009. Localization for Mobile Underwater Acoustic Sensor Networks, under review.

[50] **Royer, E.M. and Toh, C.**, 1999. A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks, *IEEE Personal Communications*, April, 46 – 55.

[51] **Akkaya, K. and Younis, M.**, 2005. A survey on routing protocols for wireless sensor networks, *Ad Hoc Networks*, **3(3)**, 325 – 349.

[52] **Mauve, M.**, **Widmer, J. and Hartenstein, H.**, 2001. A survey on position-based routing in mobile ad hoc networks, *IEEE Network Magazine*, Nov/Dec, **15(6)**, 30–39.

[53] **Akyildiz, I.F.**, **Su, W.**, **Sankarasubramaniam, Y. and Cayirci, E.**, 2002. A Survey on Sensor Networks, *IEEE Communications Magazine*, Aug., **40(8)**, 102–114.

[54] **Ko, Y. and Vaidya, N.H.**, 2000. Location-aided routing (LAR) in mobile ad hoc networks, *Wirel. Netw.*, **6(4)**, 307–321.

[55] **Vahdat, A. and Becker, D.**, 2000. Epidemic routing for partially connected ad hoc networks, Technical Report CS-200006, Duke University, April.

[56] **Lindgren, A.**, **Doria, A. and Schelén, O.**, 2003. Probabilistic routing in intermittently connected networks, *SIGMOBILE Mob. Comput. Commun. Rev.*, **7(3)**, 19–20.

[57] **Kulik, J.**, **Heinzelman, W. and Balakrishnan, H.**, 2002. Negotiation-based protocols for disseminating information in wireless sensor networks, *Wirel. Netw.*, **8(2/3)**, 169–185.

[58] **Shah, R.**, **Roy, S.**, **Jain, S. and Brunette, W.**, 2003. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, IEEE SNPA Workshop, May.

[59] **Juang, P.**, **Oki, H.**, **Wang, Y.**, **Martonosi, M.**, **Peh, L.S. and Rubenstein, D.**, 2002. Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with ZebraNet, *SIGARCH Comput. Archit. News*, **30(5)**, 96–107.

[60] **Zhao, W.**, **A., M. and Zegura, E.**, 2004. A message ferrying approach for data delivery in sparse mobile ad hoc networks, MobiHoc '04: Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing, Roppongi Hills, Tokyo, Japan, pp. 187–198.

[61] **Chen, Z.D.**, **Kung, H. and Vlah, D.**, 2001. Ad hoc relay wireless networks over moving vehicles on highways, MobiHoc '01: Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing, Long Beach, CA, USA, pp. 247–250.

[62] **Fall, K.**, 2003. A delay-tolerant network architecture for challenged internets, SIGCOMM '03: Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications, Karlsruhe, Germany, pp. 27–34.

[63] **Feng, K.**, **Hsu, C. and Lu, T.**, 2006. Velocity-Assisted Predictive Mobility and Location-Aware Routing Protocols for Mobile Ad Hoc Networks, preprint, January.

[64] **Gerla, M.**, **Lee, Y.Z.**, **Zhou, B.**, **Chen, J. and Caruso, A.**, 2006. Direction Forwarding for Highly Mobile, Large Scale Ad Hoc Networks, *IFIP International Federation for Information Processing*, 357–366.

[65] **Namboodiri, V. and Gao, L.**, preprint. Prediction Based Routing Protocol for Vehicular Ad Hoc Networks.

[66] **J.M.Montana**, **M.Stojanovic and M.Zorzi**, 2008. Focused Beam Routing protocol for Underwater Acoustic Networks, Third ACM International Workshop on Underwater Networks (WUWNeT'08, September.

[67] **Pompili, D.**, **Melodia, T. and Akyildiz, I.F.**, 2006. Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks, MobiCom '06, Los Angeles, CA, USA, pp. 298–309.

[68] **Gopi, S.**, **Kannan, G.**, **Desai, U. and Merchant, S.**, 2008. Energy Optimized Path Unaware Layered Routing Protocol for Underwater Sensor Networks, IEEE GLOBECOM 2008, December, pp. 1–6.

[69] **Gopi, S.**, **Kannan, G.**, **Chander, D.**, **Desai, U. and Merchant, S.**, 2008. Path Unaware Layered Routing Protocol for Underwater Sensor Networks, IEEE ICC 2008, May.

[70] **Domingo, M.C. and Prior, R.**, 2008. Energy analysis of routing protocols for underwater wireless sensor networks, *Comput. Commun.*, **31(6)**, 1227–1238.

[71] **Chen, D. and Varshney, P.K.**, 2007. A survey of void handling techniques for geographic routing in wireless networks, *IEEE Communications Surveys and Tutorials*, **9(1)**.

[72] **Nicolaou, N.**, **See, A.**, **Xie, P.**, **Cui, J. and Maggiorini, D.**, 2007. Improving the Robustness of Location-Based Routing for Underwater Sensor Networks, In Proceedings of IEEE OCEANS'07, Aberdeen, Scotland, June 18-21.

[73] **Xie, P. and Cui, J.**, 2007. Poster Abstract: Void Avoidance in Mobile Underwater Sensor Networks, WUWNET'07, Montreal,QC, September.

[74] **Lee, P. and Seah, W.**, 2007. A Comparison of Two Data Delivery Schemes for Underwater Sensor Networks, OCEANS 2007, June, pp. 1–6.

[75] **Yan, H.**, **Shi, Z.J. and Cui, J.**, 2008. DBR: Depth-Based Routing for Underwater Sensor Networks, NETWORKING 2008 Ad Hoc and Sensor Networks, Wireless Networks, Next Generation Internet, may, volume 4982/2008, pp. 72–86.

[76] **Guo, Z.**, **Colombi, G.**, **Wang, B.**, **Cui, J.**, **Maggiorini, D. and Rossi, G.**, 2008. Adaptive Routing in Underwater Delay/Disruption Tolerant Sensor Networks, *Wireless on Demand Network Systems and Services, 2008. WONS 2008. Fifth Annual Conference on*, Jan., 31–39.

[77] **Carlson, E.A.**, **Beaujean, P.P. and An, E.**, 2006. Location-Aware Routing Protocol for Underwater Acoustic Networks, Proceedings of the OCEANS 2006, Boston, MA, USA, Sept., pp. 1–6.

[78] **Sun, P.**, **Lee, P. and Seah, W.**, 2007. Efficient Data Delivery with Packet Cloning for Underwater Sensor Networks, Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, April, pp. 34–41.

[79] **Small, T. and Haas, Z.J.**, 2003. The shared wireless infostation model: a new ad hoc networking paradigm (or where there is a whale, there is a way), MobiHoc '03: Proceedings of the 4th ACM international symposium on Mobile ad hoc networking & computing, Annapolis, Maryland, USA, pp. 233–244.

[80] **Magistretti, E.**, **Kong, J.**, **Lee, U.**, **Gerla, M.**, **Bellavista, P. and Corradi, A.**, 2007. A Mobile Delay-tolerant Approach to Long-term Energy-efficient Underwater Sensor Networking, IEEE Wireless Communications and Networking Conference (WCNC), March 11-15.

[81] **Pedlosky, J.**, 1996. *Ocean Circulation Theory*, Springer-Verlag, Heidelberg.

[82] **Bower, A.S.**, 1991. A Simple Kinematic Mechanism for Mixing Fluid Parcels across a Meandering Jet, *J. Phys. Ocean.*, **21(1)**, 173–180.

[83] **Ottino, J.M.**, 1989. *The Kinematics of Mixing: Stretching, Chaos, and Transport*, Cambridge Texts in Applied Mathematics, Cambridge University Press.

[84] **Caruso, A.**, **Paparella, F.**, **Vieira, L.**, **Erol, M. and Gerla, M.**, 2008. Meandering Current Model and its Application to Underwater Sensor Networks, INFOCOM'08, Phoenix,AZ US, pp. 221–225.

[85] **Cencini, M.**, **Lacorata, G.**, **Vulpiani, A. and Zambianchi, E.**, 1999. Mixing in a Meandering Jet: a Markovian Approximation, *J. Phys. Oceanography*, **29(10)**, 2578–2594.

[86] **Chorin, A.J. and Hald, O.H.**, 2006. *Stochastic Tools in Mathematics and Science*, Surveys and Tutorials in the Applied Mathematical Sciences, Springer, New York.

[87] **Pasquero, C.**, **Provenzale, A. and Babiano, A.**, 2001. Parameterization of dispersion in two-dimensional turbulence, *J. Fluid Mech.*, **439**, 279–303.

[88] **Langendoen, K. and Reijers, N.**, 2003. Distributed localization in wireless sensor networks: a quantitative comparison, *Computer Networks*, **43(4)**, 499–518.

[89] **Niculescu, D. and Nath, B.**, 2004. Position and Orientation in Ad Hoc Network, *Ad Hoc Networks*, **1(2)**, 133–151.

[90] **Url-9**, *<http://www.scalable-networks.com/>, accessed on 12 December 2008*.

[91] **Kim, Y.**, **Lee, J. and Helmy, A.**, 2004. Modeling and analyzing the impact of location inconsistencies on geographic routing in wireless networks, *SIGMOBILE Mob. Comput. Commun. Rev.*, **8(1)**, 48–60.

[92] **Url-9**, *<http://www.ietf.org/rfc/rfc3561.txt>, accessed on 20 November 2008*.

[93] **Das, S.R.**, **Perkins, C.E. and Belding-Royer, E.M.**, 2000. Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks, IEEE INFOCOM 2000, March, pp. 3–12.

[94] **W. E. Leland, M.S.T.**, **Willinger, W. and Wilson, D.V.**, 1993. On the Self-similar Nature of Ethernet Traffic, (extended version), IEEE/ACM Trans. on Networking, volume 2, pp. 1–15.

[95] **Doukhan, P.**, **Oppenheim, G. and Taqqu, M.S.**, 2003. *Theory and Applications of Long-Range Dependence*, Birkauser, Basel.

[96] **Wornell, G.**, 1996. *Signal Processing with Fractals: A Wavelet Based Approach*, Prentice Hall, NJ.

[97] **Wornell, G.W.**, 1993. Wavelet-based Representations for the 1/f Family of Fractal Processes, Proc. of IEEE, volume 81, pp. 1428–1450.

[98] **Flandrin, P.**, 1992. Wavelet Analysis and Synthesis of Fractional Brownian Motion, IEEE Trans. on Information Theory, volume 38, pp. 910–917.

[99] **Abry, P. and Veitch, D.**, 1998. Wavelet Analysis of Long Range Dependent Traffic, IEEE Trans. on Information Theory, volume 44, pp. 2–15.

[100] **Stoev, S.**, **Taqqu, M.**, **Park, C. and Marron, J.S.**, 2005. On the Wavelet Spectrum Diagnostic for Hurst Parameter Estimation in the Analysis of Internet Traffic, Computer Networks, volume 48, pp. 423–445.

[101] **Erol, M.**, **Akgul, T.**, **Oktug, S. and Baykut, S.**, 2006. On the Use of Principle Component Analysis for the Hurst Parameter Estimation of Long-Range Dependent Network Traffic, Lecture Notes on Computer Science, volume 4263, pp. 464–473.

APPENDICES

A. FURTHER RESULTS: LOCALIZATION IN STATIONARY USN

In the stationary network, underwater nodes are considered to be tethered to buoys. They do not move, they only float at a fixed position. In this chapter, we repeat the simulation settings of Chapter 5 for the stationary network.

1.0.1 Localization Success

The localization success of DNRL, PL and LSL, for a highly-connected stationary underwater sensor network is given in Fig. A.1. LSL is able to localize almost all the nodes and it outperforms the other techniques. Only when beacon percentage is 35%, DNRL approaches the localization success of LSL. PL has poor localization success as it can localize at most 70% of the underwater nodes.

In Fig. A.2, we give the localization success for a low connected stationary network. DNRL performs poorly for low beacon percentages, however, its localization ratio improves with increasing beacon percentage, and at beacon percentage 35%, it outperforms the other techniques. LSL localizes a higher number of nodes than PL at all beacon percentages. At low beacon percentages, its performance is better than DNRL.

1.0.2 Communication Overhead

In Fig. A.3, we give the communication cost for the highly-connected stationary USN and in Fig. A.4, we give the communication cost for the low-connected stationary USN. In both settings, LSL sends 10 times more packets than the other methods.

1.0.3 Localization Accuracy

In Fig. A.5 and in Figure A.6, we give the mean error ratio for the highly-connected and low-connected stationary network, respectively. The mean error ratio is less than 0.1, i.e., 18 meters for all of the schemes. At low beacon percentages LSL has slightly higher error ratio than DNRL.

1.0.4 Energy Consumption

Using the same calculations as in Chapter 5, for 100 minutes and PL and DNRL spend 20J where LSL spends at least 100J, roughly. In Figure A.7, PL and DNRL will drain the battery approximately in one year but LSL in six months for the best possible scenario (35% beacon percentage in highly-connected stationary USN.) Moreover, in Figure A.8, LSL spends 250J in the best case (35% beacon percentage) and in a low connected network and the underwater nodes last less than three months.

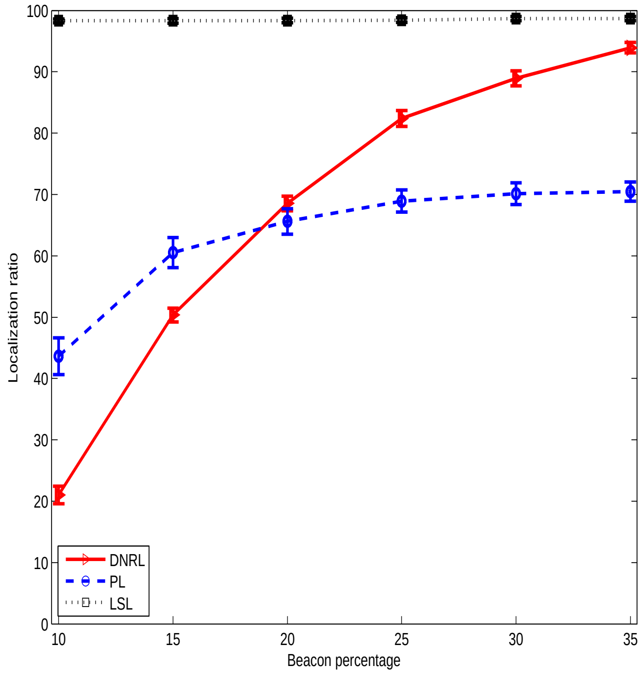

Figure A.1: Localization ratio for the DNRL, PL and LSL schemes for a highly-connected stationary underwater sensor network.

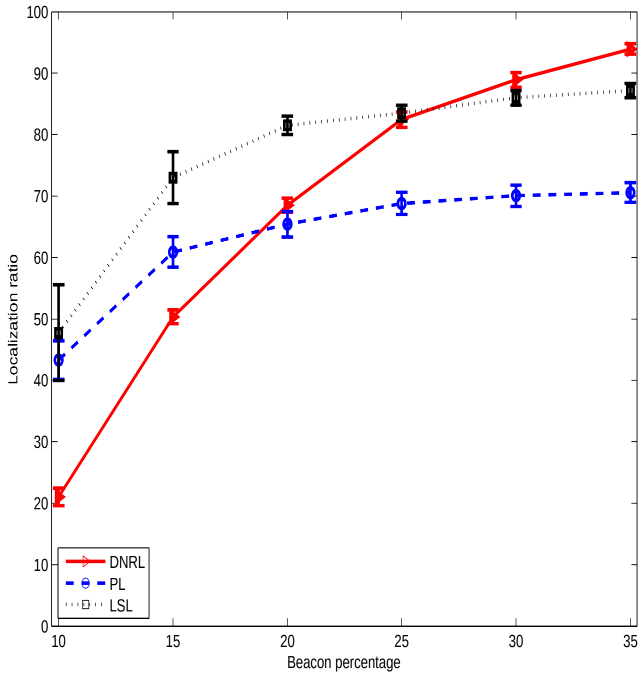

Figure A.2: Localization ratio for the DNRL, PL and LSL schemes for a low-connected stationary underwater sensor network.

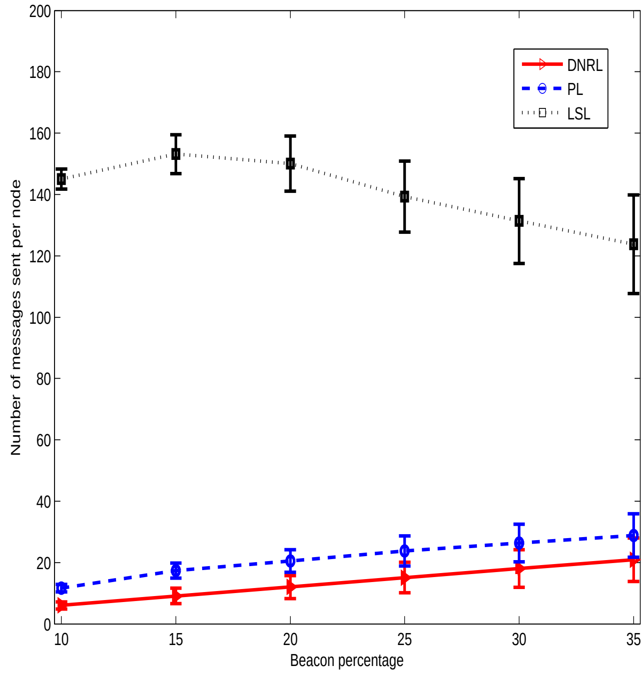

Figure A.3: Total number of sent messages per node for the DNRL, PL and LSL schemes for the highly-connected stationary underwater sensor network.

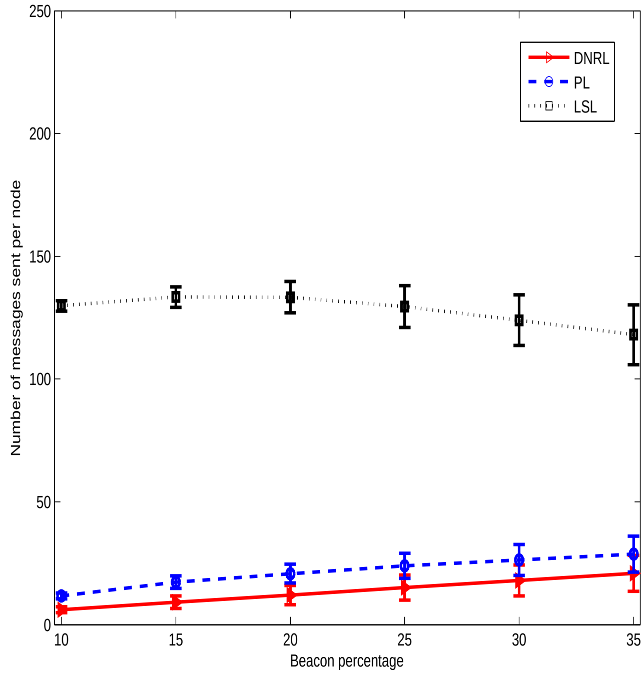

Figure A.4: Total number of sent messages per node for the DNRL, PL and LSL schemes for the highly-connected stationary underwater sensor network.

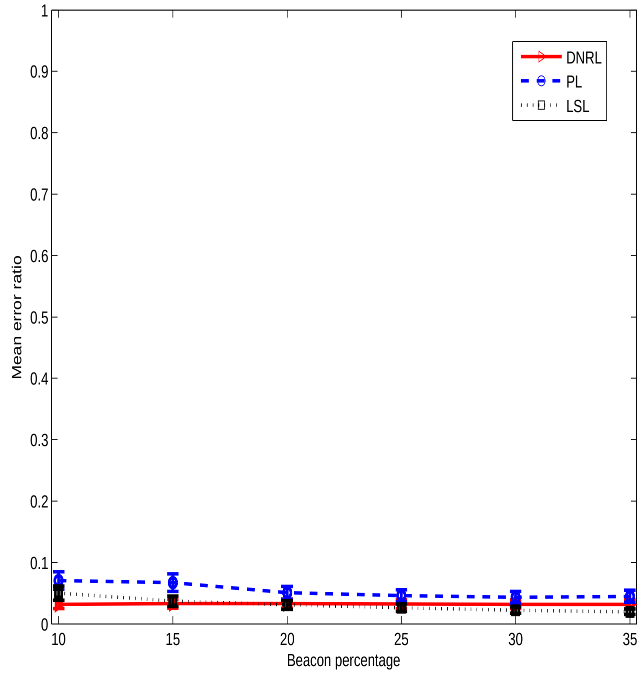

Figure A.5: Mean error ratio for the DNRL, PL and LSL schemes for a highly-connected stationary underwater sensor network.

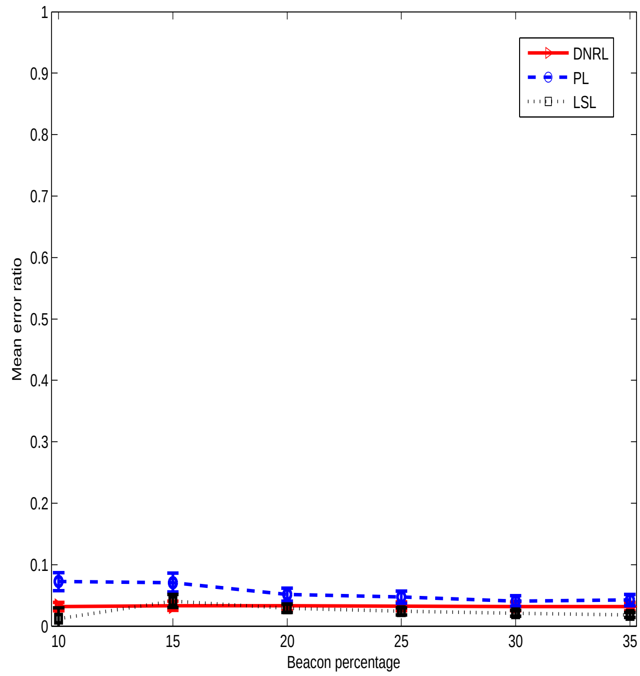

Figure A.6: Mean error ratio for the DNRL, PL and LSL schemes for a low connected stationary underwater sensor network.

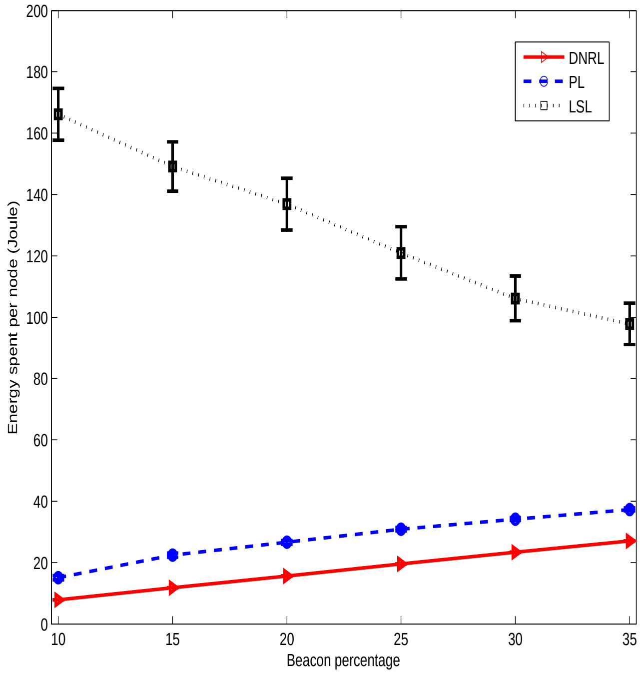

Figure A.7: Energy consumption per node for the DNRL, PL and LSL schemes for a high connected stationary underwater sensor network.

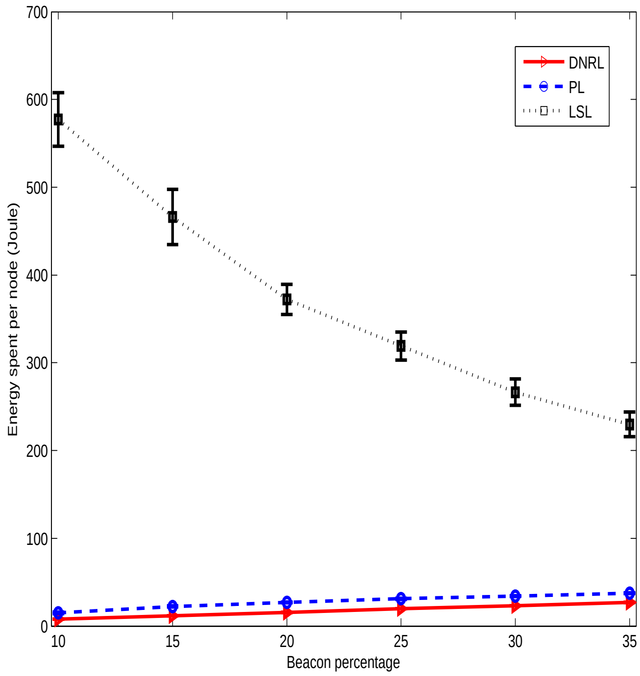

Figure A.8: Energy consumption per node for the DNRL, PL and LSL schemes for a high connected stationary underwater sensor network.

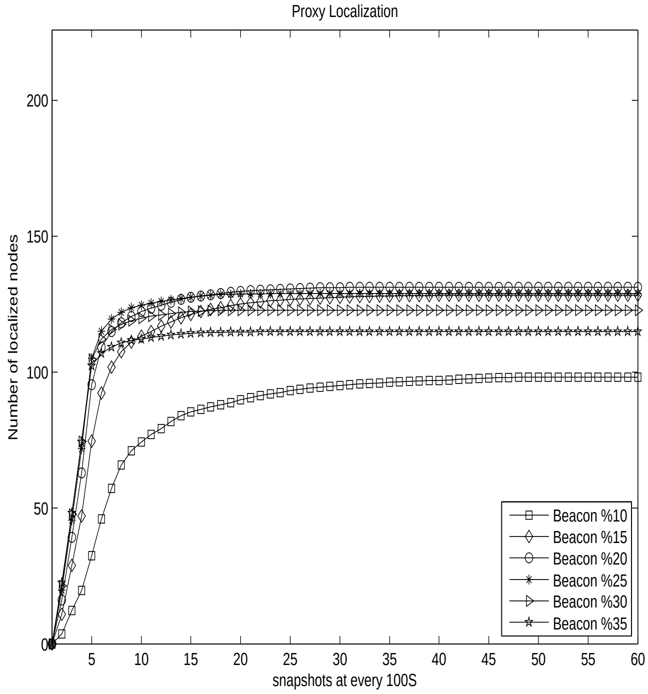

Figure A.9: Number of localized nodes versus time taken in 100s snapshots for PL method under a highly-connected stationary USN.

1.0.5 Evolution of Localization

In Figure A.9, we give the evolution of the number of localized nodes with respect to time using the PL method for the highly-connected stationary USN. The number of localized nodes saturates after 1000s at high beacon percentages. This holds for low-connected USN as seen from Figure A.10. Moreover, 1000 seconds is enough for DNRL as seen from Figures A.11 and A.12.

In Figure A.13, it takes less than 500s using the LSL method for highly-connected stationary network. For a low-connected network, only beacon percentages over 25% are able to localize a significant portion of the nodes within 500s as given in Figure A.14. For lower beacon percentages, it may take longer than 3000s.

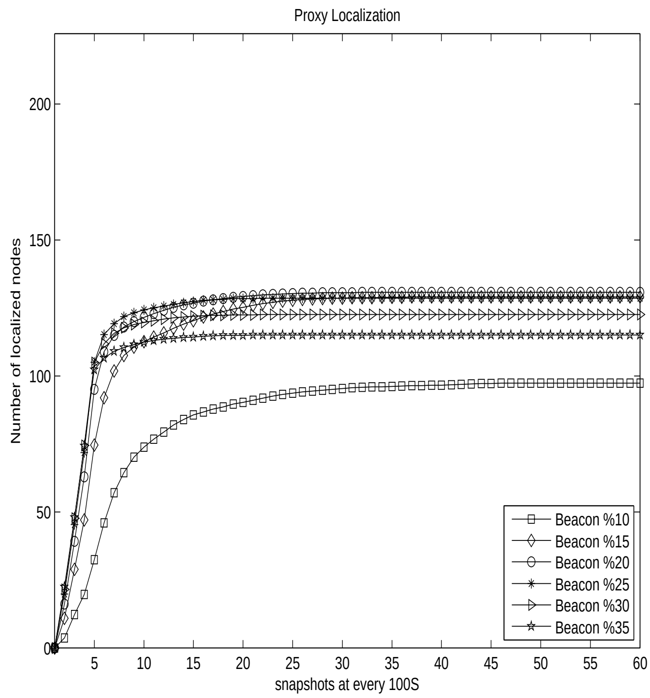

Figure A.10: Number of localized nodes versus time taken in 100s snapshots for PL method under a low-connected stationary USN.

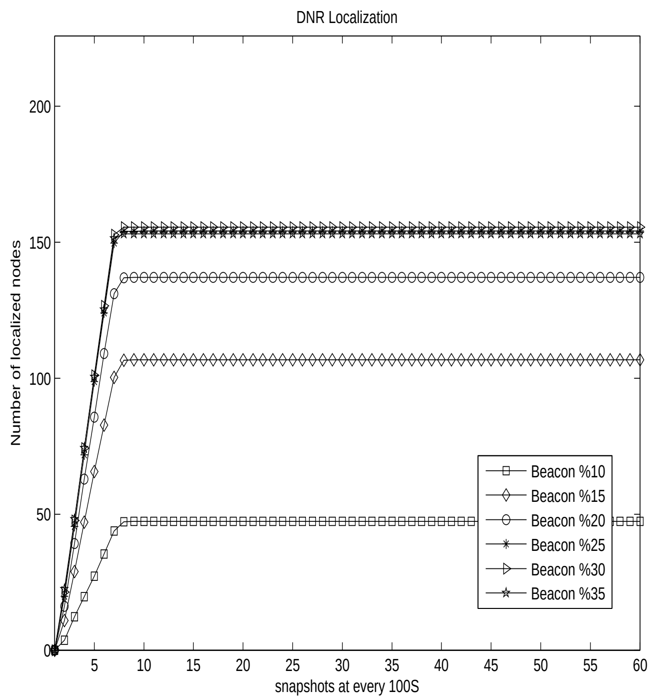

Figure A.11: Number of localized nodes versus time taken in 100s snapshots for DNR method under a highly-connected stationary USN.

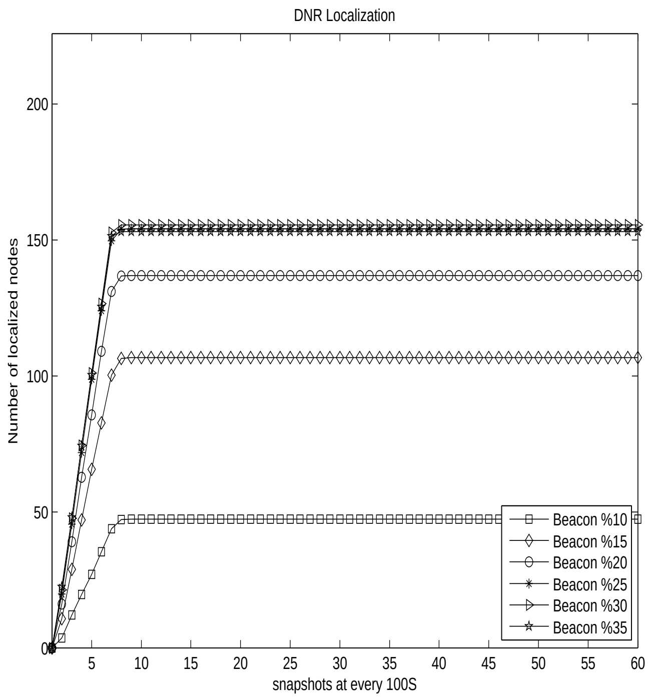

Figure A.12: Number of localized nodes versus time taken in 100s snapshots for DNR method under a low-connected stationary USN.

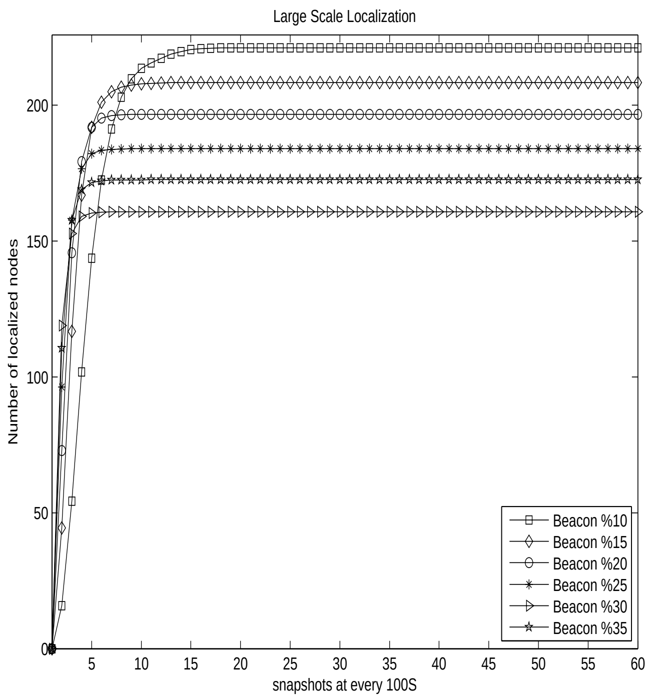

Figure A.13: Number of localized nodes versus time taken in 100s snapshots for LSL method under a highly-connected stationary USN.

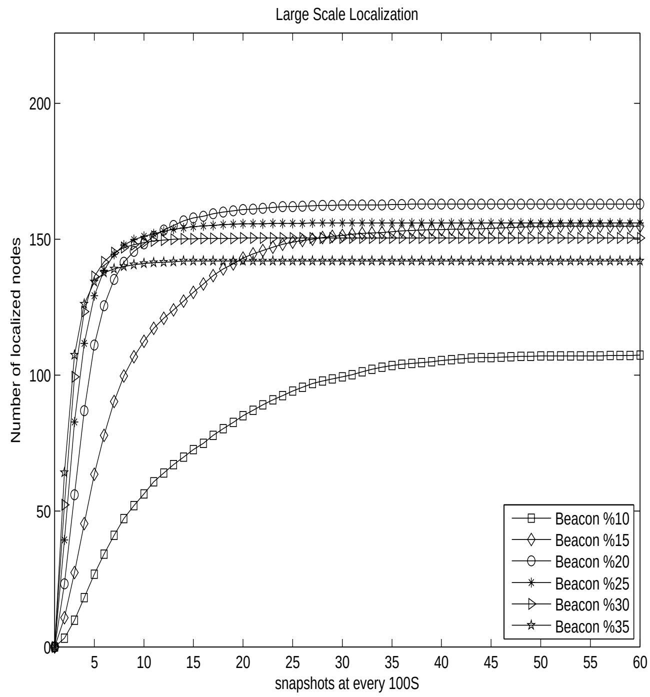

Figure A.14: Number of localized nodes versus time taken in 100s snapshots for LSL method under a sparsely-connected stationary USN.

B. PACKET TRACE CHARACTERISTICS

In this chapter, we analyze the aggregate packet traces generated by the sensor nodes. Each sensor node periodically sends packet to the sink node. On the intermediate nodes these packets are queued together with the packets of other sensors. Several nodes are on the remote parts of the network topology while some nodes are on the favorite paths. Due to packet aggregation at those nodes, the statistical properties of the traces needs to be studied. We investigate if the packet trace is self-similar.

The self-similarity of the IP network traffic has been recognized since 1990s [94] and there is a wide literature of analyses originating from these initial observations both in the computer networks and signal processing fields.

The statistical behavior of Statistically Self-Similar (SSS) processes is does not change under scaling. That means, an SSS random process, $x(t)$, can be defined as with the scaling equation [95]:

$$x(t) =^{d} a^{-H} x(at) \qquad \textbf{(B.1)}$$

where a is a positive real constant, $=^{d}$ denotes the equality of finite-dimensional distributions and H is the self-similarity parameter. There have been a large number of studies on the estimation of the H parameter. This parameter is critical in determining the correlation structure of a self-similar process. The correlation relation affects the behavior of the packet traces at the queues. A Long-Range Dependent (LRD) packet trace, introduces packets in bursts and hence causes more packet drops than uncorrelated packet arrivals. A process is LRD if $0.5 < H < 1$ and Short-Range Dependent (SRD) if $0 < H < 0.5$. For $H = 1/2$ the process is uncorrelated.

In signal processing field, self-similar processes are widely called as $1/f$ processes due to their measured spectral behavior [96]. Their spectrum obeys a power-law relationship, i.e.,

$$S_x(\omega) \sim \sigma_x^2 |\omega|^{-\gamma} \qquad \textbf{(B.2)}$$

where σ_x^2 is the variance and $S_x(\omega)$ is the empirical power spectrum of $x(t)$, ω is the angular frequency and γ is the spectral exponent [97].

Multiple interpretations of a process in different domains have led to various estimation methods of H, defined in time, frequency, wavelet and eigen domains. The wavelet Based Method (WBM) has been a popular tool in analyzing the scaling behavior of $1/f$ processes [97–99]. It has been widely used by the networking community and applied to various Internet traces [100, 101]. We use the public available codes from [99]. The wavelet transform of a $1/f$ process, $x(n)$ is:

$$x_k^m = \sum_j x(j)\psi_k^m(j) \quad \textbf{(B.3)}$$

where x_k^m are the wavelet coefficients and $\psi_k^m(n)$ are the normalized dilations (m) and translations (k) of the mother wavelet, $\psi(n)$. These coefficients are mutually uncorrelated, zero-mean, Gaussian random variables with variances following a power-law:

$$var\{x_k^m\} = \sigma^2 2^{-\gamma m} \quad \textbf{(B.4)}$$

where γ is the spectral exponent [97]. Clearly, γ is estimated from the progression of the variances of the wavelet coefficients by taking the logarithm of both sides of (B.4).

We analyze the packet trace of the busiest node in a single run. The node is on the most preferred path to sink. The packet trace collected at node 13 is given in Figure B.1. The distribution of the packet trace is given in Figure B.2. The distribution for the packet trace is Gaussian.

We apply the wavelet based estimator in Figure B.3. The Hurst parameter is estimated as 0.329 which shows SRD behaviour.

To verify the SRD we check the spectrum, the Power spectrum is given in Figure B.4

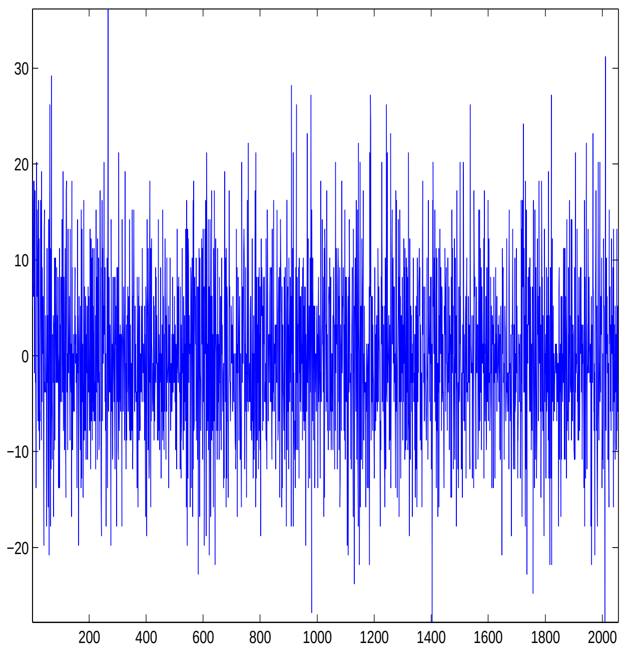

Figure B.1: Aggregated packet trace at node 13.

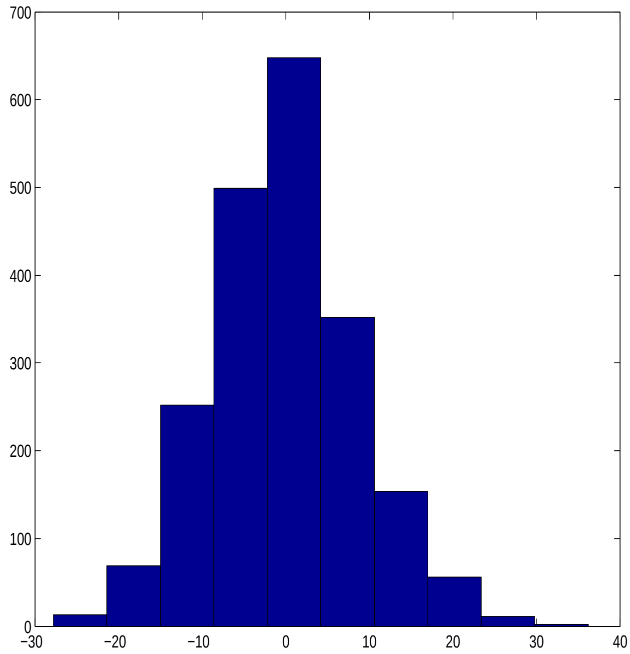

Figure B.2: The distribution of the packet trace at node 13.

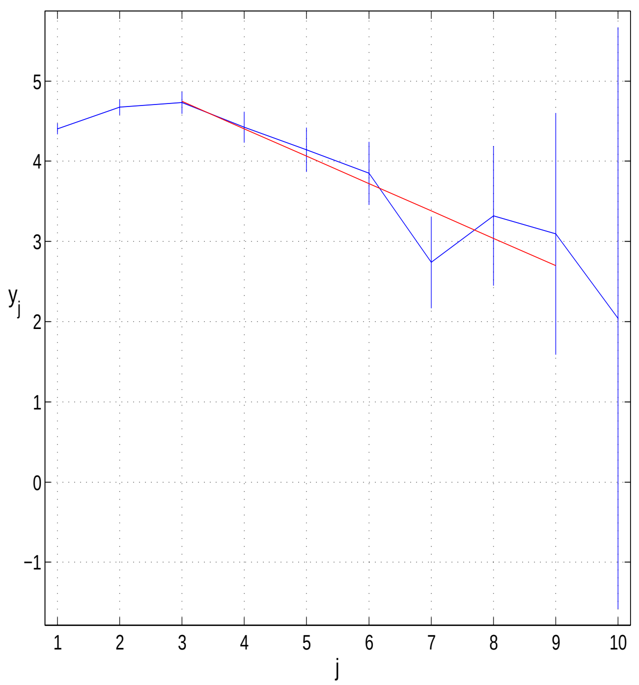

Figure B.3: The wavelet estimator for the packet trace at node 13.

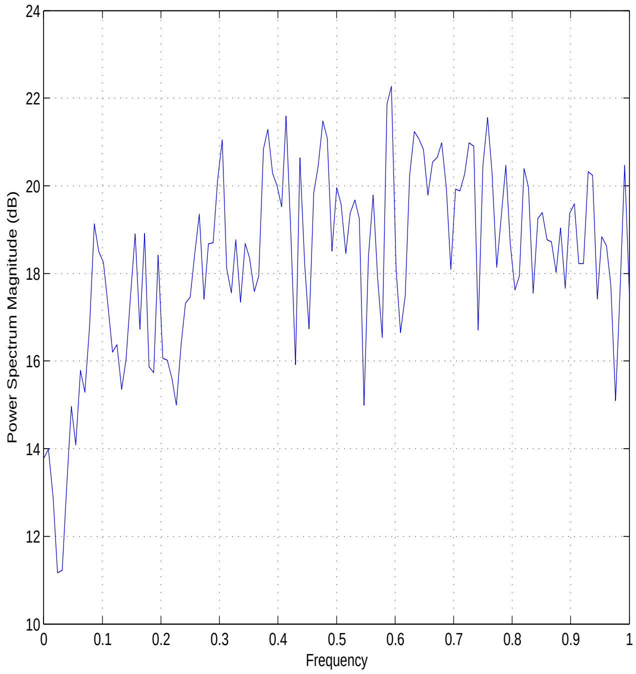

Figure B.4: The power spectrum of the packet trace at node 13.

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Publications:

Journal Papers

• **Erol M.**, Oktug S., Vieira L. , Gerla M., 2009: Localization for Mobile Underwater Acoustic Sensor Networks, *under review*.

• **Erol M.**, Akgül T., Oktug S., Baykut S. 2006: On the Use of Principle Component Analysis for the Hurst Parameter Estimation of Long-Range Dependent Network Traffic, *Lecture Notes on Computer Science*, vol.4263, pp. 464-473.

International Conference Papers

• Kuruoglu S., **Erol M.**, Oktug S., 2009: Localization in Wireless Sensor Networks with Range Measurement Errors, *in Proc. The Fifth Advanced International Conference on Telecommunications (AICT)*, Venice, Italy, May 2009.

• **Erol M.**, Vieira L., Caruso A., Paparella F., Gerla M., Oktug S., 2008: Multi Stage Underwater Sensor Localization Using Mobile Beacons, *The Second International Workshop on Under Water Sensors and Systems (in conjunction with the Second International Conference on Sensor Technologies and Applications (SENSORCOMM'08)*, Cap Esterel, France, August 2008.

• Caruso A., Paparella F., L. Vieira, **Erol M.**, Gerla M., 2008: The Meandering Current Mobility Model and its Impact on Underwater Mobile Sensor Networks, *IEEE INFOCOM*, Phoenix USA, April 2008.

• **Erol M.**, Oktug S., 2008: A Localization and Routing Framework for Mobile Underwater Sensor Networks, *IEEE INFOCOM Student Workshop*, Phoenix USA, April 2008.

• **Erol M.**, Vieira L., Gerla M., 2007: Localization with Dive'N'Rise (DNR) Beacons for Underwater Acoustic Sensor Networks, *The Second ACM International Workshop on UnderWater Networks WUWNet (in conjunction with ACM MobiCom 2007)*, Montreal, Canada, September 2007.

• **Erol M.**, Vieira L., Gerla M., 2007: AUV-Aided Localization for Underwater Sensor Networks, *WASA special track on Underwater Sensor Networks*, Chicago, USA, August 2007.

• Cevizci I., **Erol M.**, Oktug S., 2006: Analysis of Multi-Player Online Game Traffic Based on Self-similarity, *Netgames 06*, Singapore, October 2006.

• Baykut S., **Erol M.**, Akgül T., 2006: Estimation of the Spectral Exponent of 1/f Process corrupted by White Noise, *European Signal Processing Conference (EUSIPCO)*, Florence, Italy, September 2006.

• **Erol M.**, Oktug S., Akgül T., 2005: Self-Similarity of AQM Filtered Traffic, *Proc. of International Working Conference on Performance Modelling and Evaluation of Heterogeneous Networks (HET-NETs)*, Ilkley, England, July 2005.

• Baykut S., Ozkurt T. E., **Erol M.**, Akgül T., 2005: The Influence of a Single Tone Sinusoid Over Hurst Estimators, *Proc. of European Signal Processing Conference (EUSIPCO)*, Turkey, September 2005.

National Conference Papers

• **Erol M.**, Oktug S., 2009: Localization in Underwater Sensor Networks (Sualtı Duyarga Ağlarında Konumlandırma), *Proc. of IEEE 17th Signal Processing and Communications Applications Conference (IEEE Sinyal İşleme ve Uygulamaları Kurultayı)*, Turkey, April 2009.

• **Erol M.**, Oktug S., 2008: A Localization Protocol for Underwater Sensor Networks, (Sualti Duyarga Ağları İçin Konumlandirma (SDAK) Protokolü) , *4th Defense Technologies Conference (4. Savunma Teknolojileri Kongresi-SAVTEK)*, pp. 257-265, Ankara, Turkey, June 2008.

• Baykut S., **Erol M.**, Ozkurt T. E., Akgül T., 2005: The Estimation of H for fBm Processes: a Comparative Study, *IEEE 13. Sinyal Isleme Kurultayi (Signal Processing and Applications Conference)*, Erciyes, Turkey, May 2005.